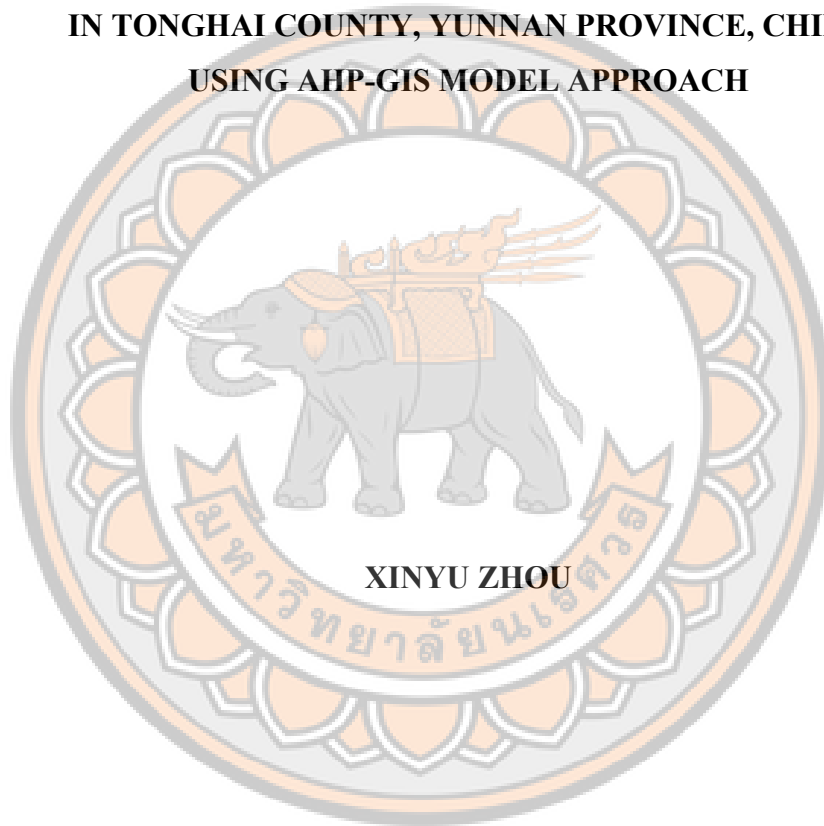




**SELECTING THE VEGETABLE GROWING AREAS
IN TONGHAI COUNTY, YUNNAN PROVINCE, CHINA
USING AHP-GIS MODEL APPROACH**



**An Independent Study Submitted in Partial Fulfillment
of the Requirements for the Master of Science Degree
in Logistics and Digital Supply Chain**

2026

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Independent Study entitled “Selecting the Vegetable Growing Areas in Tonghai
County, Yunnan Province, China Using AHP-GIS Model Approach”

By Xinyu Zhou

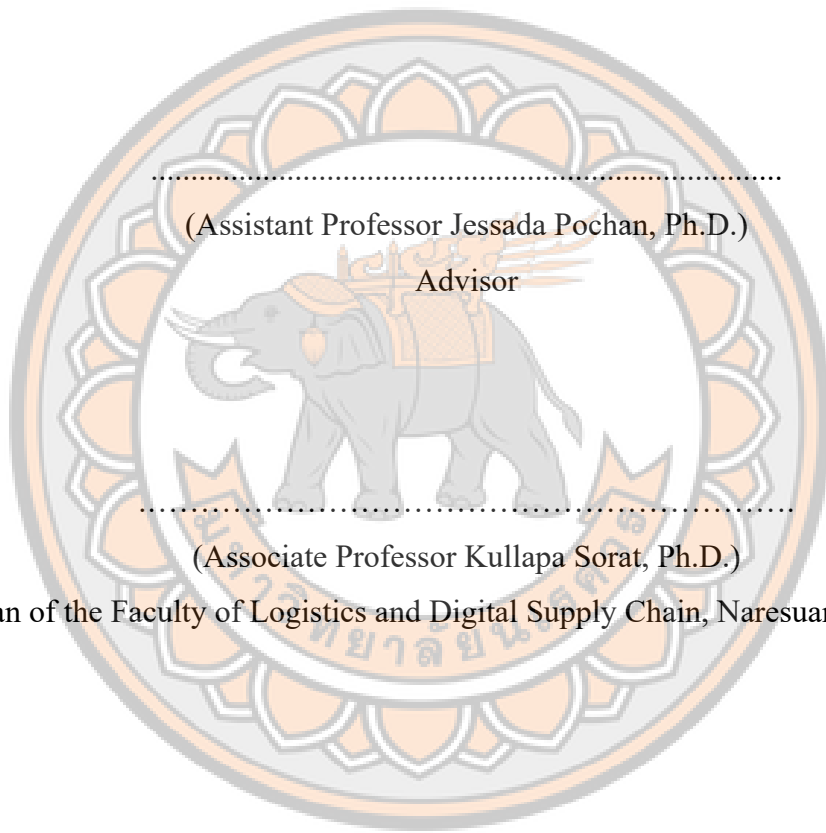
has been approved by the Logistics and Digital Supply Chain Faculty
as partial fulfillment of the requirements
for the Master of Science Degree in Logistics and Digital Supply Chain
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Title SELECTING THE VEGETABLE GROWING AREAS IN
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Keywords vegetable growing-area selection; AHP-GIS; supply-chain
accessibility; Tonghai County

ABSTRACT

Tonghai County is an important export-oriented vegetable production base in Yunnan Province, China. Because vegetables are perishable and highly dependent on efficient logistics, growing-area selection should consider both natural production conditions and supply-chain accessibility. This study developed an AHP-GIS model using nine natural, economic, and social indicators. GIS was used for standardization, weighted overlay, suitability classification, and constraint masking, with water bodies and their 200 m buffer zones treated as restricted areas.

The results showed that soil organic matter and travel time to core export markets had the highest weights. After constraint exclusion, the combined High and Very High Suitability area covered 22,960.80 ha, accounting for 33.19% of the non-restricted evaluation area. These areas were concentrated mainly around Xingmeng, Sijie, Xiushan, and Yangguang. Sensitivity analysis showed that the absolute relative change in high-quality suitable area ranged from 0.17% to 2.50%, indicating relatively good model robustness.

The findings provide spatial support for optimizing vegetable production and supply-chain infrastructure in Tonghai County.

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As I reach the end of this thesis, my master's journey is also ending. Looking back on this period of study, research, and life, there were busy days, pressure, moments of uncertainty, and times of exhaustion. Yet, more than anything, there were growth, learning, kindness, support, and companionship along the way. Completing this thesis was never the result of my efforts alone. I would therefore like to express my sincere gratitude to everyone who has offered me guidance, care, support, and encouragement throughout this journey.

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whatever happened, there was a home to which I could return. Thank you for respecting my choices, for quietly supporting me as I explored a wider world, and for allowing me to pursue what I wanted to achieve. It was your understanding and support that gave me the courage to leave my familiar surroundings, study abroad, and continue until this point.

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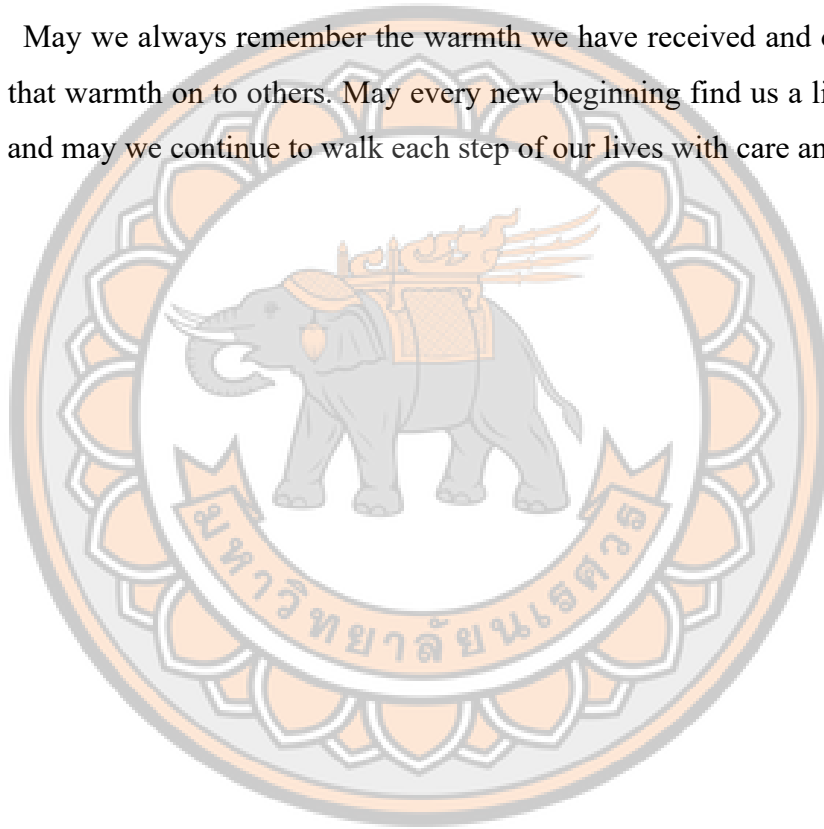
For me, this experience of studying abroad has left behind far more than a thesis and a degree. It has made me realize more clearly that growth rarely happens in one extraordinary moment; instead, it is hidden in countless ordinary days. It taught me how to face unfamiliar situations, how to become more independent, how to look for solutions during difficulty and uncertainty, and how to keep going a little longer even when I felt tired. The moments that once seemed long and difficult have now become an irreplaceable part of this chapter of my life.

There is a line from the Chinese television series *My Own Swordsman* (Wulin Waizhuan) that I have always liked: “Life should be lived one step at a time, and things should be done little by little.” Looking back, there was perhaps no single extraordinary step along the way. Most of the time, it was simply a matter of solving one problem and then completing the next task: revising again, starting over again, and reminding myself each time to keep going. Through these small and steady efforts, I gradually found myself arriving at a place I had once hoped to reach.

As this thesis comes to an end, my master's journey is also reaching its conclusion. Yet what is most worth remembering is not simply the fact that I have "finished," but the many wonderful people I met along the way, the kindness I received, and the person I have gradually become—more determined and more composed than when I first began. Once again, I would like to thank everyone who has been part of this journey and everyone who has offered me help, understanding, care, and companionship. I would also like to thank the version of myself who stumbled at times, but never truly gave up and eventually made it this far.

May we always remember the warmth we have received and one day be able to pass that warmth on to others. May every new beginning find us a little braver than before, and may we continue to walk each step of our lives with care and sincerity.

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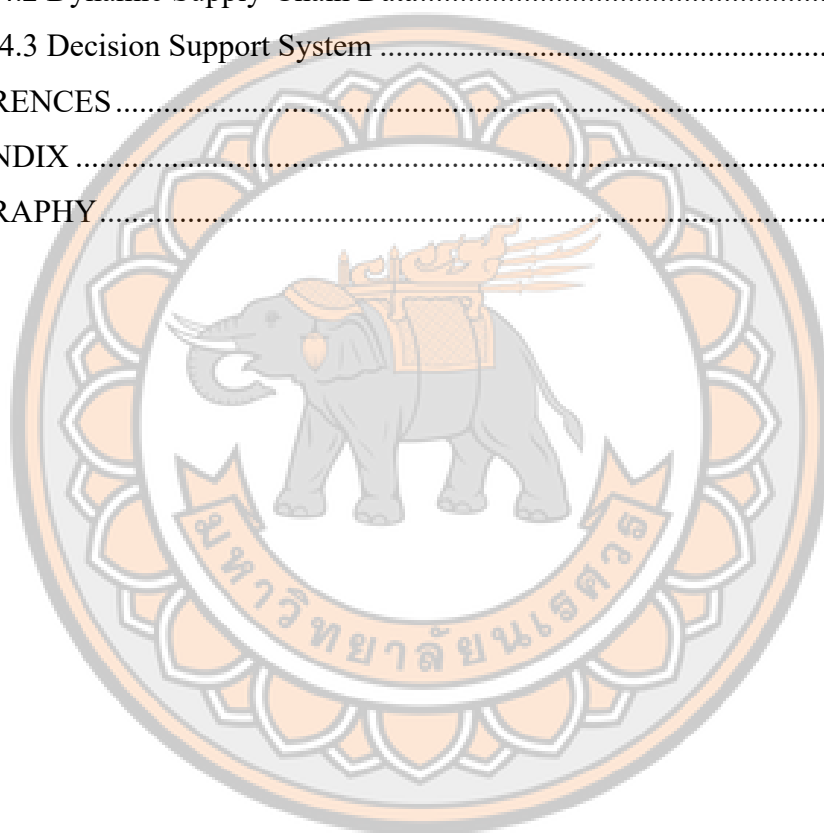
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CHAPTER I

INTRODUCTION

1.1 Research Background

1.1.1 The Status and Sustainable Development Challenges of Tonghai County's Vegetable Industry

Located in the heart of central Yunnan, Tonghai County spans approximately 720 square kilometers. Situated within the lake basin region of the Central Yunnan Plateau, the county features flat, expansive terrain, fertile soil, and excellent irrigation conditions, providing ideal natural environments for diverse crops—particularly vegetables. Long celebrated as the "Vegetable Capital of Central Yunnan," Tonghai stands as one of the province's most vital vegetable growing and export bases. Its unique natural ecology and geographical advantages not only solidify Tonghai's industrial foundation as the "Vegetable Capital of Central Yunnan" but also position it as a pivotal player in the national "South-to-North Vegetable Transport" supply chain, boasting stable supply capacity and significant brand influence.

The county's terrain, dominated by lake basin plains, synergizes with its multi-tiered climate to establish a production pattern centered on winter and spring crops while enabling year-round supply. Concurrently, the integration of surrounding trunk transportation routes with provincial capital nodes enhances its reach to wholesale markets both within and outside the province.

Climate-wise, Tonghai enjoys an average annual temperature of 16.3°C, annual precipitation of approximately 904 mm, and about 2,235 hours of sunshine per year. Its extended frost-free period and pronounced diurnal temperature variation provide natural advantages for high-quality off-season vegetable production. These factors not only enhance the marketability and taste of vegetables but also boost the competitiveness of agricultural products in the national market.

From an industrial development perspective, Tonghai County has established a large-scale facility agriculture and commercial vegetable-growing system. Vegetable Areas remain consistently high, with production steadily increasing. Key

products include tomatoes, peppers, cowpeas, and cauliflower. These vegetables not only meet local demand but are also extensively distributed to cities like Beijing, Shanghai, Guangzhou, and Chengdu, forming a vital component of China's vegetable supply chain.

Furthermore, the development of Tonghai's vegetable industry has driven increases in farmers' incomes and rural economic prosperity. Statistical data indicates that the number of agricultural operators, vegetable output value, and employment absorption capacity in Tonghai County have all shown sustained growth, making a significant contribution to the disposable income of county residents.

However, against the dual backdrop of increasing demands for vegetable quality and supply chain efficiency in domestic and international markets, coupled with intensifying constraints from agricultural modernization and resource-environmental limitations, the sustainable development of Tonghai's vegetable industry faces severe challenges. On one hand, rising market expectations for vegetable quality and safety necessitate more scientific and standardized production practices (L. Bai et al., 2023; Qiu et al., 2020). On the other hand, tightening resource and environmental constraints, coupled with prominent land use conflicts, make achieving efficient vegetable growing layouts while ensuring ecological security an urgent issue (X. Wang, 2023).

The selection of sites for modern agricultural production bases is fundamentally a complex spatial decision-making problem that integrates natural laws, economic efficiency, and social policies. Traditional "experience-based site selection" methods often rely on the subjective judgment of managers, lacking systematicity and replicability, and are prone to decision-making biases. In large-scale vegetable production areas like Tonghai County, the absence of scientific site selection models can lead to the following issues:

1. Conflict between natural conditions and production: Neglecting natural factors like topography, soil, and water resources may result in unstable yields or crop failure in unsuitable areas (Han et al., 2021a).

2. Insufficient economic efficiency: Failure to incorporate transportation, market distance, and labor factors may result in high shipping costs and slow market responsiveness, thereby weakening industrial competitiveness (Ran & Chen, 2023).

3. Ecological Red Line Conflicts: Disregarding regulatory requirements like ecological conservation red lines and permanent basic farmland may trigger policy risks and ecological damage(X. Wang, 2023).

4. Insufficient interdepartmental coordination: The absence of a unified indicator system often leads to fragmented and conflicting spatial planning due to different government departments acting independently.

Therefore, traditional experiential or single-dimensional site selection methods are increasingly inadequate for meeting Tonghai County's modernization and upgrading needs in its vegetable industry. There is an urgent need to establish a systematic, scientific, and reproducible site selection decision support system that integrates natural suitability, economic feasibility, social acceptability, and ecological safety to guide precise industrial layout and efficient development.

1.1.2 The Necessity of Applying the AHP-GIS Integrated Approach from a Supply Chain Perspective

To address these challenges, this study introduces an integrated approach combining the Analytic Hierarchy Process (AHP) with a supply chain perspective and Geographic Information Systems (GIS). The integrated application of AHP-GIS provides robust methodological support for tackling this complex spatial decision-making problem. Specifically, AHP decomposes complex site selection problems into layers of objectives, criteria, and indicators. Through pairwise comparisons, it quantifies expert judgments as weights to determine the relative importance of each factor (Saaty, 2008). GIS excels at integrating multi-source spatial data, performing standardization, weighted overlay, and visualization to intuitively display the comprehensive advantages and disadvantages of different regions(Paul A.Longley, 2014). Their integration forms a comprehensive “standardization-weighting-mapping” workflow, widely applied in fields such as agricultural land suitability analysis (Han et al., 2021a; Pramanik, 2016) .

For production areas like Tonghai County, which primarily focus on "export sales," decisions regarding the layout of production bases cannot be isolated from the supply chain network. Therefore, incorporating a supply chain perspective is crucial for optimizing site selection models and enhancing their practical guidance value. The competitiveness of the vegetable industry has expanded from individual production stages to encompass the efficiency and resilience of the entire supply chain

system. Given the perishable nature, strong seasonality, and high time-sensitivity of vegetable products, the layout of production bases must not rely solely on natural conditions but must also consider supply chain connectivity and logistics efficiency (K. Y. Wang & Yip, 2018).

Specifically, the sophistication of cold chain systems directly determines the loss rate and product quality of vegetables from farm to market. Research indicates that China's fruit and vegetable cold chain infrastructure exhibits regional disparities, with room for improvement in production-area refrigeration and node facilities in the southwest region (K. Y. Wang & Yip, 2018). Therefore, in Tonghai's site selection study, proximity to cold chain nodes must be incorporated as a key factor within the evaluation metric system.

Concurrently, for time-sensitive off-season vegetables, transportation conditions not only affect shipping costs but also directly determine whether products can reach target markets at optimal times. Research by (Ran & Chen, 2023) indicates that in fresh agricultural supply chains, transport time exhibits a tight coupling relationship with preservation inputs/losses, making market accessibility efficiency a crucial criterion for evaluating base site selection.

Therefore, incorporating transportation accessibility metrics (expanded from linear distance to road network travel time) into site selection models not only reduces logistics expenses but also enhances the industry's overall responsiveness (Ran & Chen, 2023; Zhu et al., 2023).

Thus, when constructing a vegetable production base evaluation system, "production suitability" and "supply chain efficiency" must be treated as equally core criteria. In other words, site selection should not only address "can it be cultivated?" but also resolve "can it be sold efficiently?" For instance, among plots with similar natural conditions, areas closer to highway/rail freight hubs and local cold chain centers, coupled with shorter network travel times to core markets (such as first-tier cities in North/East China), often possess higher comprehensive value.

Incorporating supply chain factors into vegetable base location models effectively resolves the issue of "suitable on paper but impractical in reality." For Tonghai County, this perspective facilitates the construction of an integrated "production-cold chain-market" industrial chain, thereby enhancing the competitiveness

and sustainability of its vegetable industry nationwide. Simultaneously, this comprehensive framework provides a basis for coordinated decision-making by government departments regarding land use, transportation planning, and cold chain infrastructure development.

1.2 Research Motivation

1.2.1 Driven by Practical Needs

Tonghai County's vegetable industry is at a critical juncture of transformation and upgrading, facing dual challenges of enhancing industrial competitiveness and achieving sustainable development. At the industrial level, intensifying market competition and evolving consumer demands render the expansion-only development model unsustainable. Optimizing spatial layout is essential to improve resource efficiency and industrial profitability. For farmers' income growth, scientifically selected locations help mitigate natural and market risks, stabilize income streams, and provide robust support for rural revitalization. Regarding ecological conservation, incorporating constraints like ecological redlines into the model prevents conflicts between industrial development and environmental protection at the source, enabling green development.

Like most perishable agricultural production areas, the spatial layout of Tonghai County's vegetable base must address not only "whether growing is feasible" but also "whether target markets can be reached with lower time costs and losses." Research indicates a significant coupling between transportation time and preservation costs/quality loss. If site selection fails to model network time costs, cold chain service accessibility, and market reach efficiency, it often leads to discrepancies where locations appear suitable on maps but prove impractical (Ran & Chen, 2023; Zhu et al., 2023).

Therefore, scientifically driven site selection guided by supply chain performance is the core driver for Tonghai's industrial upgrading: among plots with similar natural suitability, those closer to cold storage/pre-cooling centers, faster access to expressway/rail freight hubs, and shorter transport times to core markets should receive higher weighting in comprehensive rankings (Han et al., 2021a; J. Xu & Jiao, 2024).

For farmer income growth, scientific site selection quantifies both natural risks (climate-soil-water) and market risks (time-price-return rates), reducing misjudgments in investing in "highly suitable but logistically weak" sites. This enhances per-unit-area returns and income stability (Han et al., 2021a; Kılıc et al., 2022). For ecological conservation, treating ecological protection red lines, permanent basic farmland, and nature reserves as "veto-power" constraints prevents spatial conflicts while directing limited constructive resources to compliant, high-priority areas (X. Wang, 2023). From a governance perspective, establishing verifiable and auditable outcomes under unified data standards, tiered thresholds, and weighted sources facilitates interdepartmental coordination and policy implementation (Merino-Benítez et al., 2023; Topuz & Deniz, 2023).

In summary, the practical urgency can be summarized as: supply chain efficiency-driven spatial restructuring, farmer income-targeted risk convergence, and compliance optimization within ecological boundaries. These three imperatives necessitate Tonghai's adoption of an explainable, replicable, and auditable model-based site selection approach. This entails integrating both constraint and scoring factors within a unified evaluation framework while explicitly spatializing supply chain indicators (Han et al., 2021; Xu et al., 2024).

1.2.2 Opportunities for Theoretical and Methodological Advancement

In recent years, the maturation of multi-criteria decision-making methods and geographic information technologies, coupled with the integration of supply chain management concepts into agriculture, has opened new avenues for addressing these complex decision-making challenges. The established application of AHP-GIS methods provides technical support for systematic site selection, while the incorporation of a supply chain perspective offers novel insights into location studies. These methodological advancements enable the development of scientifically sound yet practical site selection models, providing crucial theoretical foundations and methodological references for this research.

On one hand, AHP demonstrates significant advantages in interpretability and consistency verification for multi-criteria land rights confirmation at the county level. It transforms implicit expertise into explicit weights through expert pairwise comparisons and consistency ratios (CR). On the other hand, GIS provides a

comprehensive toolchain for standardizing multi-source spatial data, weighted layer combination (WLC), and zoned representation. This enables the dual-layer structure of "constraints + scoring" to achieve excellent engineering operability (Han et al., 2021a; J. Xu & Jiao, 2024). Within this framework, ecological redlines/basic farmland serve as the constraint layer for masking, while "slope-soil-water sources" and "network time-cold chain accessibility-market reachability" form the scoring layer. After unified directional alignment, these layers undergo WLC overlay supplemented by sensitivity/robustness testing (Merino-Benítez et al., 2023; Topuz & Deniz, 2023).

Concurrently, recent reviews and empirical studies indicate that spatializing supply chain factors represents a frontier direction in agricultural site selection: rasterizing and unifying indicators such as road network time, cold chain node service radius and capacity, and target market delivery time impedance for WLC integration significantly enhances the alignment between "model suitability" and "operational performance" (freshness, loss rate, price differential) (Ran & Chen, 2023; Zhu et al., 2023). Methodologically, AHP can also be combined with variants like fuzzy AHP to address linguistic uncertainties in expert judgments, validated in plot-to-county-level assessments across multiple crops (Kilic et al., 2022). Overall, the "trinity" of AHP-GIS-supply chain factors is emerging as a replicable paradigm for county-level site selection research, providing a mature template for this study's implementation in Tonghai County (Makkulawu et al., 2023).

1.3 Research Questions

Building upon the analysis of research motivations, this study must further clarify the core issues to be addressed. Defining research questions not only determines the study's direction but also provides logical support for selecting research methods and structuring the paper. Considering Tonghai County's industrial characteristics, gaps in existing research, and the constraints of this study, the research questions can be summarized in three aspects.

Question 1: How to construct a comprehensive evaluation index system suitable for site selection in Yunnan's highland vegetable growing areas?

The selection of agricultural production bases fundamentally involves a multi-factor comprehensive evaluation. As a perishable and time-sensitive agricultural

product, vegetables exhibit high dependency on natural conditions, transportation infrastructure, social environment, and ecological conservation requirements. Therefore, the primary core issue this study must address is how to develop a scientific, comprehensive, and Tonghai-specific indicator system (Han et al., 2021a; Pramanik, 2016).

Question 2: How to determine the weights of each site selection factor using the Analytic Hierarchy Process (AHP)?

After establishing the indicator system, the second challenge is assigning reasonable weights to these indicators. Different factors carry varying importance in site selection—for instance, transportation accessibility and soil fertility may outweigh slope aspect or gradient. Thus, scientifically determining weights is a critical step in site selection research (Saaty, 2008).

Question 3: How can AHP results be integrated with GIS spatial analysis techniques to identify and select the optimal vegetable growing areas in Tonghai County?

After establishing the indicator system and weights, the third research question addresses how to integrate these results with GIS technology to generate suitability distribution maps. This process further identifies Tonghai County's optimal vegetable growing areas, providing scientific references for policy formulation and industrial planning (Makkulawu et al., 2023; Yang & Yao, 2024).

1.4 Research Objectives

Building upon the analysis of the research background, motivation, and questions, this study further clarifies its objectives. These objectives not only concretize the research questions but also serve as the core guidance for methodology and research pathways. Considering the actual development of Tonghai County's vegetable industry and the methodological design of this study, the following three research objectives are established.

Objective 1: The primary objective is to identify key factors for selecting vegetable growing areas through a systematic literature review. Existing research indicates that land suitability analysis often requires integrating multidimensional indicators spanning natural, economic, social, and ecological dimensions (Han et al.,

2021a; Pramanik, 2016). Therefore, this study will focus on establishing an "indicator-constraint" list covering major factors through literature review and synthesis.

Objective 2: After identifying the site selection factors, the next step is to determine their relative importance in the selection process. To this end, this study employs the Analytic Hierarchy Process (AHP) to assign weights to each factor (Saaty, 2008), providing a basis for subsequent weighted overlay in GIS. Numerous studies have demonstrated that applying AHP to agricultural base site selection and land suitability assessment effectively enhances model scientific rigor and transparency (Makkulawu et al., 2023).

Objective 3: Finally, the outcomes from the first two objectives will be integrated with GIS-based multi-criteria decision-making (GIS-MCDM) to identify and select the most suitable vegetable growing areas in Tonghai County. This objective not only provides spatial decision support for the development of Tonghai County's vegetable industry but also offers methodological references and application paradigms for other plateau agricultural bases in Yunnan Province and across China (Xue et al., 2023; Yang & Yao, 2024).

By achieving these objectives, this study not only addresses the research questions posed earlier but also provides actionable references for Tonghai County's vegetable industry planning and contributes to scientific site selection research for plateau agriculture.

1.5 Research Scope

1.5.1 Scope of Vegetable Types

This study focuses on the site selection of major commercial vegetable growing areas in Tonghai County rather than on all vegetable species. Based on the current development characteristics of Tonghai County's vegetable industry, tomatoes, peppers, cowpeas, and cauliflower are regarded as representative vegetable types in this study. These vegetables constitute important components of the county's commercial vegetable production and distribution system. Therefore, the study mainly evaluates the common spatial conditions affecting the location of major commercial vegetable growing areas at the county scale, rather than establishing separate crop-specific suitability models for each vegetable species.

1.5.2 Analytical Boundaries

This study is positioned as a county-scale strategic assessment of vegetable growing-area selection. It aims to identify areas with relatively favorable conditions within Tonghai County and to provide spatial support for vegetable-industry planning rather than detailed farm- or parcel-level decision making. The specific site-selection factors and their measurement methods are identified and developed through the literature review and methodological procedures presented in the subsequent chapters. For variables that cannot be directly observed at a fine spatial scale, the analysis is limited to representations that can be consistently applied at the county scale. Accordingly, labor-related conditions are considered at an aggregated spatial level rather than through direct measurement of individual agricultural workers or households.

1.6 Research Framework

1.6.1 Overall Research Approach

The overall research approach follows the scientific logic of "problem identification — theoretical analysis—methodology development — empirical research — result synthesis." By constructing a multi-criteria decision-making (MCDM) model based on the Analytic Hierarchy Process (AHP) and Geographic Information System (GIS), this study achieves the scientific site selection and spatial optimization of vegetable growing areas in Tonghai County, Yunnan Province.

This study comprises three core phases:

Phase I: Identification of Site Selection Factors and Construction of an Indicator System. Through literature review, key influencing factors for vegetable growing site selection are identified, and a comprehensive indicator system encompassing four dimensions—natural, economic, social, and ecological—is established (Han et al., 2021a; Pramanik, 2016).

Phase 2: Determination of Indicator Weights and Model Establishment. The Analytic Hierarchy Process (AHP) was employed to establish a judgment matrix and calculate indicator weights. Consistency tests were conducted to form a quantifiable decision weighting system (Makkulawu et al., 2023; Saaty, 2008).

Phase 3: Spatial Overlay Analysis and Suitability Identification. Building upon the outcomes of the first two phases, the GIS-MCDM (Multi-Criteria Decision Making) method was applied to spatialize, standardize, and weight-overlay all factors, calculating the comprehensive suitability index for each region within Tonghai County. Subsequently, the natural breakpoint method (Jenks) was applied to classify suitability levels, identifying core areas most suitable for vegetable growing. This process generated suitability distribution maps and spatial decision recommendations (Xue et al., 2023; Yang & Yao, 2024).

1.6.2 Research Structure and Chapter Logic

This study comprises five chapters, with their logical relationships illustrated in Table 1. Each chapter serves one or more research objectives, forming a closed-loop logic of "objective-method-result."

Table 1 Research Structure and Chapter Logic

No.	Chapter	Main Content	Corresponding
1	Introduction	Outlines the research background, motivation, problem statement, objectives, and overall framework	Establish the research foundation
2	Literature Review	Review research findings on agricultural base site selection, AHP, GIS, and supply chain perspectives to identify theoretical gaps and research trends	Objective 1: Identify site selection factors
3	Research Methodology	Establish an evaluation indicator system, determine AHP weights, and construct a comprehensive evaluation model	Objective 2: Construct Evaluation System and Determine Weights
4	Case Study	Using Tonghai County as a case study, applying the AHP -GIS model to	Objective 3: Identify optimal areas and conduct

No.	Chapter	Main Content	Corresponding
		conduct spatial overlay analysis and suitability identification	comparative analysis with current conditions
5	Conclusions and Outlook	Summarize key research findings and innovations, propose policy recommendations and future research directions	Research Summary and Extension



CHAPTER II

LITERATURE REVIEW

2.1 Theoretical Evolution and Practical Paradigms in Agricultural Site Selection Research

Agricultural site selection research centers on identifying the optimal spatial match between land resources and specific agricultural activities. This section systematically reviews the evolution of theoretical frameworks in this field and organizes research paradigms at both macro and micro scales, thereby laying the theoretical foundation for constructing a site-selection research framework for vegetable growing areas in Tonghai County.

2.1.1 Theoretical Evolution from Land Evaluation to Multi-Criteria Decision-Making

Agricultural site selection research originates from the need to identify optimal matching relationships between agricultural activities and land resources under multiple natural, economic, and policy constraints. The initial theoretical foundation traces back to the FAO's 1970s "Land Evaluation Framework," whose significant contribution lies in distinguishing "land characteristics" from "land use types." By establishing standardized suitability classification and evaluation processes based on factors like yield, inputs, and environmental constraints, it transformed agricultural land assessment from empirical practice to standardized methodology (FAO, 1976).

This framework established common criteria for determining the "feasibility, suitability, and unsuitability" of various crops and provided an institutional starting point for subsequent methodological updates.

By the 1990s, the widespread adoption of Geographic Information Systems (GIS) and Remote Sensing (RS) technologies enabled researchers to transition from qualitative assessments toward spatial and quantitative modelling. The unified management and overlay analysis of multi-source spatial data rapidly introduced Multi-Criteria Decision Making (MCDM) into agricultural site selection (Malczewski, 2006).

Within the MCDM family, the Analytic Hierarchy Process (AHP) gained widespread adoption due to its ability to translate expert judgments into pairwise comparison matrices and subsequently calculate relative weights (Saaty, 2008). The pivotal shift in this phase was the transition from "single-factor threshold judgment" to "multi-factor comprehensive trade-offs." Researchers no longer merely asked "whether a site is suitable," but further compared "which site is relatively better," emphasizing the compromise and balance among multiple elements. This enabled comparability among many regional studies and made data visualization and results communication more intuitive and readily accepted by policy departments (Eastman, 2012; Pramanik, 2016).

In the literature context, early discrimination based on "single-factor thresholds" has gradually been replaced by multi-criteria decision-making paradigms involving "multi-factor trade-offs" (Malczewski, 2006). Among these, the Analytic Hierarchy Process (AHP) maps expert knowledge into a judgment matrix through pairwise comparisons and employs the eigenvalue method to derive weights, ensuring judgment consistency and testability under the condition $CR < 0.1$ (Ishizaka & Labib, 2011). The "interpretability" and "auditability" of this method are particularly suited for practical applications at the county scale and for cross-departmental collaboration.

Compared to the traditional FAO framework, which focuses primarily on the "static suitability" of natural and production factors, GIS-MCDA integrates data organization, rasterization, reclassification, weighted overlay, and visualization into an end-to-end technical workflow (Drobne & Lisec, 2009; Malczewski, 2006). This facilitates a complete shift in agricultural site selection from "paper maps and experiential judgment" to "digital maps and verifiable calculations," providing a technical foundation for policy alignment and project implementation. This study will leverage the "interpretable + verifiable" strengths of AHP while implementing uniform resolution, standardized thresholds, and transparent weight calculations within GIS. This ensures the traceability and verifiability of Tonghai County's vegetable base site selection outcomes during departmental reviews (Ishizaka & Labib, 2011; Malczewski, 2006).

2.1.2 Research Scale Differentiation Between Macro Strategy and Micro Operation

The practical scale of agricultural site selection is clearly divided into macro and micro levels.

Macro-level research primarily serves national or provincial strategies, such as delineating advantageous agricultural product belts or assessing food security potential, with conclusions emphasizing pattern identification and directional guidance. For instance, the Global Agricultural Ecological Zones (GAEZ) system, jointly developed by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA), utilizes global-scale climate, soil, and topography data to simulate the potential yields of major crops under varying management practices and climate change scenarios. Its outputs are widely applied to assess global and regional food production potential and vulnerability, providing macro-level decision support for international agricultural policies and climate change responses. Such studies typically employ kilometer-level data resolution to reveal large-scale spatial patterns and trends.

Micro-level research adopts counties as the fundamental unit, focusing on implementing specific operations. County-level administrative divisions both implement higher-level strategies and directly support concrete tasks such as high-standard farmland construction, industrial park planning, cold chain node deployment, and territorial spatial management. Consequently, they prioritize data precision, unified classification standards, and operational feasibility (Juan Xu et al., 2023).

International comparisons reveal that developed countries emphasize ecosystem services, environmental constraints, and long-term resilience in county-level research (Feizizadeh & Blaschke, 2013), while developing countries prioritize food security, yield enhancement, and farmer livelihoods (Halefom & Teshome, 2019). In fresh produce and floriculture industries supplying perishable goods, micro-scale factors (county/township/parcel level)—including road network travel times, cold chain node service radii, and market accessibility—become decisive determinants (Aung & Chang, 2014).

Case studies involving perishable, high-value crops like vegetables demonstrate that incorporating both “transport time–cold chain accessibility” and “slope–soil–temperature” into county-level models significantly improves model explanatory power, with “high suitability zones” substantially overlapping existing major production areas or high-yield fields (Zhu et al., 2023). This provides a comparable reference for Tonghai County's integrated “nature–supply chain” modeling. This study unifies the county-level scale to a 30-meter grid resolution, balancing constraints and preferences from both the natural-supply and supply chain-demand ends. This ensures suitability hotspots are not only “cultivable” but also capable of “rapid, fresh, and stable sales.”

2.1.3 Global Perspectives on Site Selection Research and Application Implications

As a mature spatial decision support tool, the AHP-GIS integrated method has demonstrated its universality and flexibility through repeated validation across diverse agricultural systems, crop types, and developmental contexts worldwide. This extensive prior research provides a robust methodological foundation and factor selection reference for the implementation in Tonghai County.

Globally, site selection model development is strongly influenced by regional agricultural development priorities and crop characteristics. In temperate intensive agricultural systems of developed regions like Europe and America, research often emphasizes environmental sustainability and ecological service values.

For instance, German studies on organic farming site selection models assign higher weights to ecological factors such as distance from water source buffer zones and biodiversity conservation value (Rejaury Rahman & Saha, 2008). Conversely, in developing regions like Southeast Asia and Africa, research primarily serves food security and cash crop expansion. For instance, suitability assessments for oil palm plantations in Indonesia comprehensively evaluate soil physicochemical properties and rainfall distribution while attempting to incorporate social factors like land tenure and community acceptance into the model (Akıncı et al., 2013). These regional differences indicate that when constructing Tonghai County's model, it is essential to deeply understand its industrial positioning and development needs as a specialized export hub for plateau vegetables.

In high-time-sensitivity sectors like vegetables, fruits, and flowers, supply chain factors often carry weight comparable to key natural factors. Ethiopian flower bases significantly depend on international airport cold chain capacity and flight frequency (measurable as “time-opportunity accessibility”)(Weiss et al., 2018). This evidence supports integrating “cold chain and market time” into the suitability evaluation criteria layer.

Comparisons across crops also reveal weighting differences. Staple crops (e.g., wheat, corn) are sensitive to factors like soil depth, pH, and irrigation reliability (Pramanik, 2016), while high-value, time-sensitive crops (e.g., leafy greens, fresh fruit, cut flowers) exhibit greater sensitivity to “road network time/cold chain radius/wholesale market grade-distance” (Aung & Chang, 2014; Zhu et al., 2023).

As a key origin for the “South-to-North Vegetable Transport” initiative, Tonghai County should prioritize “time to highway or rail freight hubs,” “time to county pre-cooling or cold storage centers,” and “time to core target markets” at the core of its economic layer. These factors, alongside “slope-temperature-organic matter,” collectively determine comprehensive suitability.

2.1.4 Formation of the "Constraint-Scoring" Dual-Layer Evaluation Framework

Methodologically, agricultural site selection has progressively adopted a widely accepted "constraint-scoring" dual-layer framework. Policies or ecological red lines with "veto power"—such as ecological conservation red lines, permanent basic farmland, and water source protection areas—are treated as constraint factors and eliminated first. Subsequently, scoring factors that can be comparatively evaluated and quantified—such as soil fertility, transportation accessibility, and market distance—are standardized and weighted to generate a continuous suitability index. This process balances compliance with scientific rigor (Feizizadeh et al., 2014; Makkulawu et al., 2023).

Within a GIS environment, constraints are typically applied using Boolean masking, while scoring is overlaid using methods like weighted linear combination (WLC). Results can be visualized as contour maps of suitability and aligned with regulatory zoning categories such as "buildable," "restricted," or

"prohibited," facilitating interdepartmental coordination and project implementation (Eastman, 2012; Malczewski, 2006).

The framework's advantage lies in ensuring site selection's legal compliance through constraint factors while enabling scientific identification of relative strengths across areas via scoring factors. This has become a universal paradigm for spatial decision-making in agriculture, urban-rural planning, and ecological conservation.

The scoring layer commonly employs weighted linear combination (WLC).

Formula 2-1 Weighted Linear Combination

$$S = \sum_i w_i \cdot X_i \quad (2-1)$$

where S represents the comprehensive suitability score, X_i denotes the standardized score (e.g., 1–5 points) for factor i , and w_i is the relative weight obtained via AHP ($\sum w_i = 1$). WLC permits “compensatory decision-making,” where deficiencies in one dimension can be partially offset by strengths in others, aligning with the integrated trade-offs in agriculture-logistics-market systems (Malczewski, 2006; Yager, 1988). To express risk preferences like “conservative or aggressive,” ordered weighted averaging (OWA) can adjust compensation intensity (Yager, 1988).

For grid implementation, first perform grid multiplication with a constraint mask $M \in \{0,1\}$: $S^* = S \times M$, ensuring all “no-build zones (0)” are excluded. Then, grade S^* using the natural breakpoint method (Jenks) or quantile method to facilitate planning communication and project implementation (Jenks, 1963). Tonghai County's two-stage “constraint-scoring” process clearly distinguishes between “hard constraint compliance” and “selecting the best among the good,” enhancing transparency and interpretability during multi-departmental coordination.

2.2 Review of Key Methodologies and Technologies for Agricultural Site Selection

The integration of AHP, GIS, and MCDM represents the most prevalent and operationally feasible technical paradigm in contemporary agricultural site selection research. Rather than reiterating foundational definitions exhaustively, this section focuses on their practical strengths and common limitations in real-world applications, proposing feasible improvement directions based on existing experience.

2.2.1 Application of AHP in Weight Determination

In agricultural site selection, AHP's value lies in providing a unified "weighting language" for heterogeneous indicators. For example, indicators with vastly different dimensions, such as soil organic matter, slope, time to market, and distance to cold chain nodes—can be transformed into a common weighting system through expert pairwise comparisons, enabling comprehensive integration (Pramanik, 2016).

The pairwise comparison strategy employed by AHP aligns closely with human cognitive patterns when confronting complex decisions. By focusing solely on comparing the relative importance of two elements at a time, it proves simpler and more reliable than simultaneously weighing all factors, effectively reducing the cognitive load of decision-making.

However, the "subjective nature" of AHP remains a concern. Experts from different backgrounds may produce significantly divergent judgment matrices. Without correction, these discrepancies directly propagate into the weights and final rankings (Topuz & Deniz, 2023; Zabihi et al., 2019).

To minimize biases arising from individual subjectivity, current best practices involve forming an expert panel spanning multiple relevant fields such as agricultural science, resource environment, land planning, and logistics supply chains. Mathematical methods like geometric averaging are then employed to aggregate all experts' judgments, thereby generating a more representative and consensus-driven group decision matrix (Dong et al., 2010).

AHP calculates weights for the judgment matrix A by finding the maximum eigenvalue and corresponding eigenvector. The maximum eigenvalue $\lambda_{\max}$ and its eigenvector w are normalized to obtain the weights; Consistency is measured by $CI = (\lambda_{\max} - n)/(n - 1)$ and $CR = CI/RI$, where $CR < 0.1$ Adapted from (Ishizaka & Labib, 2011). Group AHP employs the "Arithmetic-Geometric Mean of Individual

Judgments (AIJ)” aggregation method: calculate the geometric mean of scores for each element pair, construct a group matrix, then determine weights and CR following the same procedure (Forman, 1996). This process preserves multidisciplinary knowledge while suppressing extreme judgments.

India, Ethiopia, Turkey, Iran, and others widely employ AHP to determine weights in agricultural land suitability studies, validating robustness through CR tests and sensitivity analyses (Feizizadeh & Blaschke, 2013; Halefom & Teshome, 2019; Pramanik, 2016). Tonghai County will employ the AIJ geometric mean method to aggregate diverse expert judgments from agriculture, soil science, planning, supply chain, and local management sectors, thereby mitigating single-discipline bias. CR tests and weight sensitivity analyses will be conducted to ensure the robustness and persuasiveness of the weights.

2.2.2 The Core Role of GIS in Spatial Analysis and Integration

GIS is far more than a mere mapping tool in agricultural site selection; it functions as an "operating system for spatial data." On one hand, GIS enables the overlay, clipping, resampling, and rasterization of raster and vector data from departments such as land resources, agriculture, water conservancy, and transportation within a unified coordinate system, allowing multi-source data to "speak the same language." On the other hand, it efficiently performs complex spatial calculations such as slope gradient, aspect, water system buffer areas, network accessibility, and cost distance, presenting results through intuitive maps to help governments and stakeholders reach consensus faster (Lucie Váňová, 2014; Malczewski, 2006).

It is important to emphasize that GIS network analysis functions serve as the technological cornerstone enabling the “supply chain perspective” adopted in this study. This capability precisely calculates actual travel time or costs from each candidate site to target locations—such as highway interchanges, cold storage centers, or designated wholesale markets—based on real road networks, preset driving speeds, and even terrain elevation variations. This network-based distance or time calculation far better reflects the real-world dynamics of agricultural product distribution than simple straight-line distance, making site selection evaluations more practical.

Particularly for fresh and perishable goods, simple “straight-line distance” fails to capture actual distribution costs. Increasing research shifts toward “network distance and time costs,” aligning with the mainstream definition of accessibility as “the time and cost difficulty of reaching a destination” (Geurs & Van Wee, 2004). (Weiss et al., 2018) published in *Nature*, which mapped global urban travel times, profoundly revealed the significant impact of spatiotemporal accessibility on socioeconomic development. This macro-level study corroborates the critical importance and foresight of incorporating “time cost” as a core evaluation factor in micro-level agricultural site selection.

Accordingly, employing “road network travel time” instead of “straight-line distance” in vegetable base site selection aligns not only with supply chain logic but also with consensus in spatial economics and transport geography. Tonghai County will generate time grids using “OD cost matrices or service area analysis” to access expressways/provincial highways, cold chain centers, county logistics nodes, and core export markets. These grids will serve as core cost factors in the economic layer, overlaid with WLC analysis.

2.2.3 Selection and Comparison of MCDM Methods

Within the MCDM framework, different methods emphasize distinct aspects and suit varying decision scenarios. The frequent adoption of WLC stems primarily from its “ease of understanding, communication, and verification.” WLC permits trade-offs between criteria, aligning with the intuitive notion that “weaknesses can be offset by strengths.” When incorporating risk preferences, Ordered Weighted Averages (OWA) can be introduced to express preferences for “more conservative or more aggressive” approaches, proving particularly valuable in ecologically sensitive areas or regions facing heightened policy pressures (Yager, 1988; Zabihi et al., 2019).

It is crucial to emphasize that WLC typically operates in tandem with Boolean logic—first using “constraints” to exclude “prohibited areas,” then employing “scoring” to compare “relative merits.” This approach ensures compliance with red lines while identifying “superior options within permitted development areas,” forming a common “combination strategy” in agriculture, land use, and urban-rural planning (Eastman, 2012; Feizizadeh et al., 2014).

Additionally, another technical approach to address "subjectivity" involves introducing methods like fuzzy AHP or entropy weighting or combining them with ideal solution methods such as TOPSIS for cross-validation. Some studies indicate that for indicator sets with sufficient sample observations or objective statistical characteristics, incorporating objective weighting can serve as a "secondary calibration" mechanism. This allows the comprehensive evaluation to reflect expert experience without over-reliance on it (Kılıc et al., 2022; Sathiyamurthi et al., 2024).

However, in practical county-level applications, the adoption of more complex methods requires a comprehensive balance between data quality, team collaboration costs, and departmental review difficulties. This study favors a "constraint + WLC + AHP" framework to ensure the method is "adequate, effective, and user-friendly."

2.3 Integration and Evolution from a Supply Chain Perspective

A key gap between traditional agricultural site selection and modern agricultural decision-making lies in the consideration of market and distribution channels. A significant theoretical advancement of this study is the systematic integration of a supply chain perspective into the site selection model. This shift in perspective stems from a deep understanding of the value realization process for agricultural products, particularly perishable vegetables, whose value is not only created during production but also realized or diminished during distribution.

Traditional agricultural site selection often focuses on "whether growing is feasible," while the core competitiveness of modern vegetable industries increasingly lies in "whether products can be sold stably, rapidly, and with freshness preserved." For export-oriented production areas, the Spatial layout of production bases must be "embedded" within existing or plannable supply chain networks. Factors such as cold chain capacity, network access time, market distance, and trunk route conditions directly alter the comparison between a plot being "suitable on paper" versus "feasible in reality" (Han et al., 2021a).

Quantifying supply chain factors and incorporating them into suitability models represents a frontier in recent research. For instance, in domestic Chinese research, (Ran & Chen, 2023) clearly demonstrated through mathematical modeling that

for highly perishable vegetables like leafy greens, even a one-hour increase in transport time causes a non-linear acceleration in both the rate of quality deterioration and the required preservation costs. This study theoretically quantifies the critical importance of time costs to the economic efficiency of the vegetable industry.

Correspondingly, (Zhu et al., 2023) focused on cold chain logistics network optimization, treating transit time from production bases to consumer markets as a core optimization target. They empirically demonstrated the decisive role of minimizing time costs in reducing overall losses. While African flower production bases emphasize the temporal accessibility of “airport cold chain—scheduling frequency—customs efficiency” (Weiss et al., 2018). These studies provide a robust theoretical and empirical foundation for this research to adopt key supply chain metrics such as “travel time to core export markets” as central evaluation factors.

Research on fruit and vegetable cold chains indicates that infrastructure remains unevenly distributed across regions. Mismatches between delivery timelines and cold chain capacity lead to significant losses and quality degradation, impacting marketability and final retail prices (K. Y. Wang & Yip, 2018). From a supply chain coordination perspective, transportation time is highly correlated with preservation costs. Sites closer to highway exits, logistics parks, and cold storage hubs often possess greater comprehensive advantages under identical natural conditions (Ran & Chen, 2023; Zhu et al., 2023).

This implies that incorporating the supply chain perspective into site selection models transforms the problem from a "static suitability" map into a "dynamic value chain" optimization process. The evaluation criteria expand beyond "natural endowments" to encompass the comprehensive performance of the chain: "production—preservation—transportation—time to market— price volatility—waste—net profit." This approach makes the assessment of “land quality” more aligned with the actual operational logic of production and distribution.

In summary, theoretical advancements and practical case studies worldwide converge on a single conclusion: a scientifically sound and operationally viable model for selecting vegetable cultivation zones must organically integrate natural suitability with supply chain efficiency. This study's case analysis of Tonghai County represents a systematic application and refinement of this research paradigm.

In the language of accessibility studies, this effectively embeds "opportunity accessibility" and "cost accessibility" into agricultural spatial decision-making. It treats "time cost to market" and "time cost to cold chain nodes" as key explanatory variables, favoring "network travel time" over "straight-line distance" to better approximate real-world conditions (Geurs & Van Wee, 2004; Weiss et al., 2018). In GIS implementation, these calculations can be achieved through network analysis methods like service areas, shortest time paths, or cost distance, and integrated with the weighting system derived from AHP (Lucie Váňová, 2014).

Overall, treating supply chain factors as core criteria alongside natural factors helps resolve the paradox where locations appear suitable on maps but prove unfeasible. For vegetable export-oriented regions like Tonghai County, the supply chain perspective significantly enhances the feasibility and industrial guidance value of site selection outcomes: it helps governments identify "priority-construction" cold chain nodes and connectivity corridors, while enabling enterprises to pinpoint "comprehensively optimal" plots that ensure both stable production and rapid market access.

More importantly, the supply chain perspective enhances interdepartmental coordination efficiency, aligning "industrial planning—transportation planning—cold chain planning—land use control" on a single integrated map (Han et al., 2021a; Zhu et al., 2023).

2.4 Tonghai County and Related Case Studies

Tonghai County is situated in the lake basin area of the Central Yunnan Plateau in central Yunnan Province. With its flat terrain, fertile soil, and abundant water resources, it stands as one of Yunnan's most vital vegetable production and export bases. Benefiting from unique natural ecological conditions, convenient transportation access, and long-established cultivation traditions, Tonghai has earned the reputation as "Central Yunnan's Vegetable Capital." In recent years, under the national strategy of "transporting vegetables from south to north," Tonghai County has emerged as a vital node in China's southwest region for the national vegetable supply chain. Its industrial development not only impacts local agricultural restructuring but also deeply integrates with cold-chain logistics and urban-rural supply systems.

From an industrial foundation perspective, Tonghai County ranks among the top in Yunnan Province in terms of vegetable cultivation scale, brand development, and export capacity. Vegetable planting area and total output have maintained steady growth, with exports reaching multiple Southeast Asian countries and major Chinese consumer cities (B. Xu et al., 2023). The county hosts a few registered export bases and leading enterprises, driving the sustained development of standardized and green production within the region. Concurrently, local governments and research institutions have accumulated extensive practical experience in sustainable production. For instance, experimental studies on organic fertilizer substitution, continuous cropping obstacle prevention and control, and water-saving irrigation provide technical support for enhancing vegetable quality and ecological conservation (Han et al., 2021a).

In terms of product structure, Tonghai County produces a variety of commercial vegetables, with tomatoes, peppers, cowpeas, and cauliflower among the major products. Their established production and distribution provide the practical crop context for the present study. Although individual vegetable species differ in specific agronomic requirements, this research focuses on the common spatial conditions relevant to county-scale commercial vegetable growing-area selection rather than on crop-specific physiological suitability.

However, despite existing research on Tonghai's vegetable industry's natural endowments, industrial organization, and export structure, systematic studies on spatially quantitative siting remain limited. Particularly scarce are studies deeply integrating supply chain factors (logistics and cold-chain accessibility) with GIS–AHP models. This research gap has garnered significant international attention: scholars widely acknowledge that traditional natural suitability analysis can no longer meet the timeliness and market-driven demands of modern agricultural production (Feizizadeh & Blaschke, 2013; Malczewski, 2006).

From a global perspective, different countries and industrial systems exhibit distinct priorities in agricultural site selection.

In Europe, agricultural site selection research often centers on ecological conservation and sustainable land use. For instance, in Austria and Germany, researchers employed a GIS–AHP model incorporating soil fertility, slope, water source buffer zones, and biodiversity indices as core indicators. They constructed a three-tiered

model— “ecological suitability–production potential–policy constraints”—to support spatial decisions for ecological agriculture (Feizizadeh & Blaschke, 2013). Such studies emphasize the rigidity of ecological constraints and the operational feasibility of spatial controls, reflecting a “compliance-first” planning logic.

In North America, however, site selection decisions prioritize transportation accessibility and supply chain coordination efficiency. In the U.S. Midwest grain-producing regions, multi-criteria decision models quantify road density, distance to storage centers, and transportation costs. These metrics are then overlaid with plot productivity to form an integrated “production-processing-transportation” decision framework (Drobne & Lisec, 2009). This systems-efficiency-centered approach offers valuable insights for China's southwest vegetable industry in developing cold chain infrastructure and export distribution strategies.

In Southeast and South Asian countries (e.g., Thailand, India, Vietnam), AHP–GIS models primarily serve food security and cash crop expansion.(Pramanik, 2016) using West Bengal, India as a case study, found that slope, irrigation density, and road accessibility significantly influence agricultural land suitability. Meanwhile, the importance of the “market distance” factor is increasingly recognized, reflecting the growing coupling between agriculture and supply chain systems.

In African highland countries like Ethiopia, Halefom and Teshome proposed a model incorporating climate change scenarios and social acceptability (Halefom & Teshome, 2019) . Their findings indicate that cold chain node density and transport time directly determine the regional competitiveness of high-value agricultural products such as potatoes and flowers.

These international experiences indicate that Tonghai County's vegetable industry must balance “ecological constraints” and “market accessibility” in future planning to achieve coordinated optimization of land use, production efficiency, and supply chain networks.

From an industrial perspective, significant differences exist in the weighting of factors within location models across different sectors.

Studies on fruit and vegetable export industries, such as those in Chile and Spain, identified distance to cold storage facilities and port transit time as core factors influencing fresh table grape export competitiveness, with their combined weighting

comparable to soil fertility. Similarly, (Aung & Chang, 2014) found in cold chain logistics research that product spoilage rates increase exponentially with each hour of transport delay, making time costs far more critical than traditional land factors in supply chain agriculture.

In livestock and dairy sectors, research focuses more on factors like feed supply radius and disease buffer zones (Rejaur Rahman & Saha, 2008), with model structures emphasizing the spatial balance between “ecological security and production radius.” In renewable energy crops (e.g., oil palm and sugarcane), researchers minimize transportation costs between “base–processing plant–export port” as the decision objective, constructing “energy supply chain-oriented” location models (Akıncı et al., 2013). These industry practices collectively reveal a trend: optimizing agricultural spatial layout has shifted from single natural condition evaluation to value-chain optimization.

Regarding crop types, crops with different biological and economic attributes exhibit distinct sensitivities to location model factors.

In models for staple crops (e.g., wheat, corn, rice), natural factor weights (e.g., soil depth, pH, precipitation) typically exceed 0.6, while socioeconomic factor weights are lower (Pramanik, 2016). High-value perishable crops (e.g., leafy greens, strawberries, cut flowers) exhibit the opposite trend, with composite weights for indicators like cold chain accessibility, transport time, and market distance often exceeding 0.5, reflecting extreme sensitivity to supply chain efficiency (Aung & Chang, 2014; Weiss et al., 2018). Studies on perennial crops (e.g., olives, grapes) indicate that topographic factors like slope and aspect decisively influence mechanization levels and yield stability (Malczewski, 2006). Consequently, models often incorporate “mechanical accessibility” or “slope thresholds” as constraint factors.

These findings suggest that the suitability model for Tonghai County's vegetable industry should prioritize high timeliness and value. Network travel time and cold-chain accessibility should be established as core criteria-level factors alongside climate and soil.

Methodologically, the flexibility and interpretability of the AHP–GIS–WLC integrated model provide an ideal technical pathway for county-level agricultural site selection. AHP determines factor weights through the eigenvalue method, making

decision logic verifiable and consistency quantifiable; GIS enables spatial data integration and visualization; the WLC method allows “compensatory decisions” between factors, ensuring the composite suitability reflects trade-offs between natural and economic elements (Drobne & Lisec, 2009; Eastman, 2012). This methodological framework has been validated in county-level agricultural planning across multiple countries, effectively capturing multidimensional trade-offs while generating spatial output layers compatible with planning departments.

Therefore, in the Tonghai County case, integrating the three-tier logic of “ecological constraints—supply chain efficiency—land potential” to construct an AHP–GIS multi-criteria decision model not only enables scientific evaluation of the spatial distribution advantages of vegetable production bases but also facilitates synergistic optimization with cold chain infrastructure planning.

In summary, Tonghai County's research should draw on international experience while integrating local ecological and industrial conditions to develop a comprehensive evaluation framework balancing natural suitability and supply chain accessibility. Within this framework: - Ecological red lines and permanent basic farmland serve as the constraint layer, pre-excluding unsuitable areas; - Climate, soil, and topography factors constitute the production potential layer; - Transportation networks, cold chain nodes, and market distances form the supply chain layer. The overlay of these three layers generates a comprehensive suitability index, providing scientific basis for government planning of vegetable industry spatial layout, cold chain construction, and “South-to-North Vegetable Transport” supply systems.

2.5 Systematic Literature Review and Evidence Synthesis

To strengthen the transparency and reproducibility of factor identification, a systematic literature review (SLR) was conducted to further verify and synthesize the literature support for candidate factors relevant to vegetable growing-area selection. An SLR provides a structured approach for identifying, screening, evaluating, and synthesizing existing studies related to a defined research question (Snyder, 2019). The review process was organized with reference to the PRISMA 2020 framework, which provides a transparent structure for reporting study identification, screening, eligibility assessment, and final inclusion (Page et al., 2021).

Two complementary Scopus searches were conducted to cover both agricultural land-suitability research and supply-chain accessibility related to vegetable production. The main search identified 77 records, while the supplementary supply-chain search identified 62 records, resulting in a total of 139 records. After title and abstract screening, 92 records were excluded and 47 reports were sought for retrieval. Two reports were unavailable, leaving 45 full-text studies for inclusion in the formal synthesis. The identification and screening process is shown in Figure 1.

Among the 45 included studies, 33 primarily addressed land suitability and 12 provided evidence related to supply-chain accessibility. The synthesis showed that slope received direct support from 19 studies, while annual average temperature and soil organic matter were each supported by 7 studies. Among the economic and supply-chain factors, travel time to main roads was supported by 5 studies, travel time to county-level wholesale or logistics hubs by 7 studies, travel time to cold-storage/pre-cooling/processing points by 6 studies, and travel time to core export markets by 9 studies. Agricultural labor density or agricultural employment ratio received direct support from 4 studies. Rural public service accessibility received no direct support from the included full-text studies but was retained because of its local applicability and spatial measurability. The review also supported the separate consideration of three categories of ecological and policy constraints. Literature frequency was used as descriptive evidence of factor support rather than as indicator weight, because the relative importance of the retained scoring indicators was subsequently determined independently through AHP.

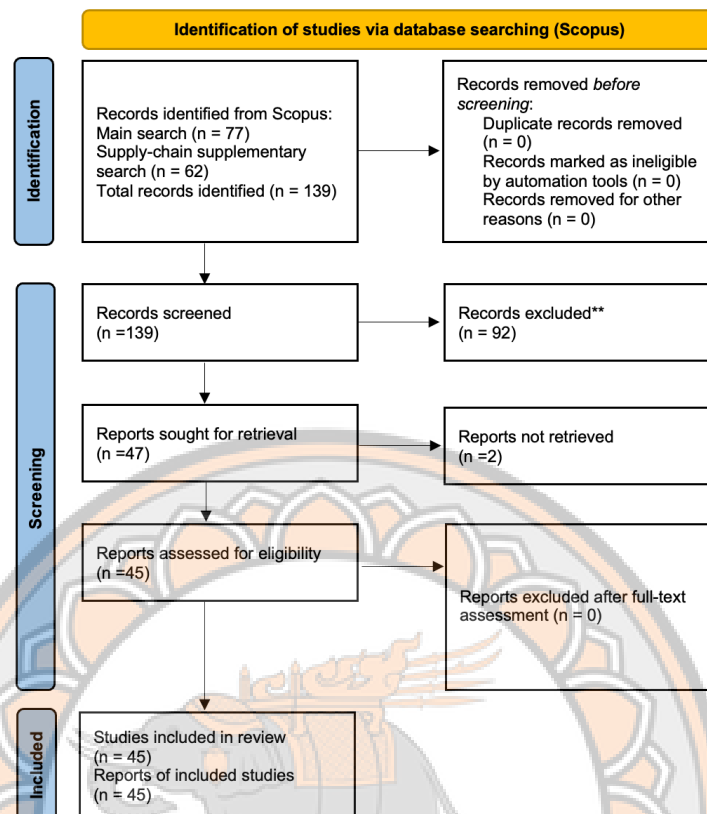


Figure 1 Identification and Screening of Studies Based on PRISMA 2020

2.6 Research Review and Positioning

A systematic review indicates that agricultural site selection research has evolved from early empirical land assessments into a scientifically grounded and operationally feasible multi-criteria decision-making system. Beginning with the FAO (1976) Land Evaluation Framework as its theoretical foundation, the introduction of GIS-MCDM facilitated a shift from static qualitative judgments to dynamic spatial quantitative analysis, gradually forming a dual-layer structure of “constraints-scoring” (Eastman, 2012; Malczewski, 2006). Within this framework, the hierarchical structure of AHP enables the comparison and weighting of indicators with different dimensions within a unified system. GIS provides a platform for spatial data integration and computation, while the WLC model achieves comprehensive evaluation of natural, economic, and social factors through weighted linear combination (Feizizadeh & Blaschke, 2013). The integration of these theories and methods has propelled

agricultural spatial decision-making from subjective experience toward a data-driven paradigm, establishing it as a core tool for modern land-use planning.

However, a review of global case studies reveals several notable shortcomings in current agricultural site selection research when addressing the “full industrial chain” demands of modern agriculture.

First, there exists a structural disconnect in research perspectives. Many studies treat “production suitability” as an endpoint, overlooking the decisive impact of supply chain and market timeliness on perishable products. For instance, case studies of Ethiopia's flower industry demonstrate that transport time to ports or airports, cold chain infrastructure density, and international flight frequency are core determinants of export competitiveness (Weiss et al., 2018). In contrast, most studies at the county level in China remain primarily focused on natural endowments, lacking systematic integration of the “production-distribution-consumption” chain.

Second, research suffers from insufficient standardization and reproducibility. Across different countries and regions, significant variations exist in data resolution, reclassification methods, and weighting approaches (Malczewski, 2006). The absence of standardized indicator systems and unified methodologies makes cross-regional comparisons challenging.

Third, model validation remains relatively weak. Many studies fail to cross-validate generated suitability maps against actual crop distribution, cold chain node locations, or transportation timelines, undermining the direct applicability of findings to policy or investment decisions (Feizizadeh & Blaschke, 2013; Han et al., 2021a).

Finally, the auditability and weight robustness of these methods require improvement. While AHP provides a structured decision-making framework, expert subjectivity remains unavoidable. Without group judgment aggregation (AIJ) and consistency checks ($CR < 0.1$), biases can easily arise (Ishizaka & Labib, 2011). Some studies also omit sensitivity analysis, making it difficult to assess the impact of weight changes on outcomes.

Addressing these limitations, this study attempts theoretical extension and methodological innovation in three aspects when applying the approach to site selection for Tonghai County's vegetable base.

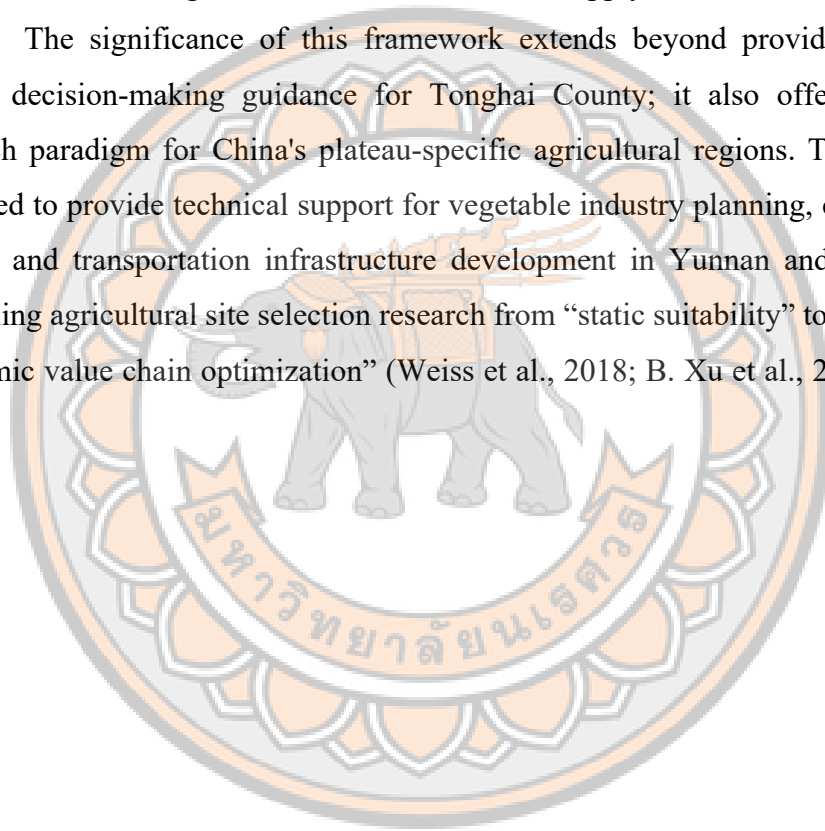
First, we establish a comprehensive evaluation system integrating natural factors and supply chain factors. Traditional models predominantly focus on natural variables such as soil, slope, and precipitation. Building upon this foundation, this study incorporates “travel time to expressways or arterial roads,” “travel time to cold chain centers and wholesale markets,” and “travel time to target consumer cities” into the economic and supply chain sub-layers. This multidimensional structure more accurately reflects the economic logic and time constraints governing the spatial distribution of the vegetable industry (Aung & Chang, 2014; Zhu et al., 2023). The GIS network analysis module generates a road network time cost raster, enabling spatial integration of natural, logistics, and market factors to ensure site selection balances “cultivability” and “accessibility.”

Second, a closed-loop “constraint-scoring-validation” model design was adopted. During model construction, ecological conservation red lines, permanent basic farmland, water source protection zones, and other restricted areas were first excluded using Boolean masking to ensure compliance. Subsequently, expert judgments were aggregated using the Aggregate Geometric Mean (AIJ) method of the Analytic Hierarchy Process (AHP), with consistency checks ($CR < 0.1$) ensuring weight reliability. Finally, the Weighted Linear Combination (WLC) method is applied for multi-factor weighted integration to generate a comprehensive suitability index. During model validation, output results undergo spatial matching analysis with Tonghai County's existing crop distribution, cold chain nodes, and main road networks. Market arrival time data further verifies model logical consistency, achieving bidirectional validation from computation to reality (Dong et al., 2010; Han et al., 2021a).

Third, emphasize methodological transparency and reproducibility. This study establishes uniform standards for data sources, normalization rules, weight determination, and classification methods. All processes are implemented within the ArcGIS environment and are reproducible. By documenting parameters and decision matrices at each step, results are ensured to be traceable and verifiable. Additionally, sensitivity analysis will be conducted at the study's conclusion to evaluate the impact of weight perturbations on the final suitability distribution, thereby validating the model's robustness and scientific validity (Feizizadeh & Blaschke, 2013; Malczewski, 2006).

In summary, this study's academic positioning lies in establishing a comprehensive model for Tonghai County that integrates natural suitability and supply chain efficiency into the county's agricultural site selection decision-making system. This model combines scientific rigor, interpretability, and practical applicability. Unlike traditional approaches focused solely on “whether cultivation is feasible,” this research emphasizes systemic objectives: “whether stable production, rapid delivery, freshness preservation, and efficiency enhancement are achievable.” This addresses the practical demands of modern agriculture's transition toward supply chain and market orientation.

The significance of this framework extends beyond providing operational spatial decision-making guidance for Tonghai County; it also offers a replicable research paradigm for China's plateau-specific agricultural regions. The findings are expected to provide technical support for vegetable industry planning, cold chain node layout, and transportation infrastructure development in Yunnan and other regions, propelling agricultural site selection research from “static suitability” to a new phase of “dynamic value chain optimization” (Weiss et al., 2018; B. Xu et al., 2023; Zhu et al., 2023).



CHAPTER III

RESEARCH METHODOLOGY

3.1 Research Approach

As discussed in Chapter 2, existing research on agricultural site selection—particularly in highland vegetable-producing regions like Tonghai County—suffers from fragmented perspectives, insufficient reproducibility, and inadequate consideration of supply chain dimensions. To systematically address these issues, this chapter aims to construct an integrated evaluation model combining the Analytic Hierarchy Process (AHP) with Geographic Information Systems (GIS). This model emphasizes scientific rigor, operational feasibility, and reproducibility of results to fill the research gaps.

This study rigorously follows a logical progressive framework: "factor identification—weight determination—spatial evaluation." First, a systematic literature review identifies location factors spanning natural, economic, social, and ecological dimensions to construct a comprehensive evaluation indicator system. Next, the Analytic Hierarchy Process (AHP) determines the relative weights of each factor. Finally, integrating GIS spatial analysis with multi-criteria decision-making techniques completes the spatial suitability evaluation for Tonghai County's vegetable growing areas. The entire technical approach is illustrated in Figure 2, which will guide the detailed discussion of each methodological step in this chapter.

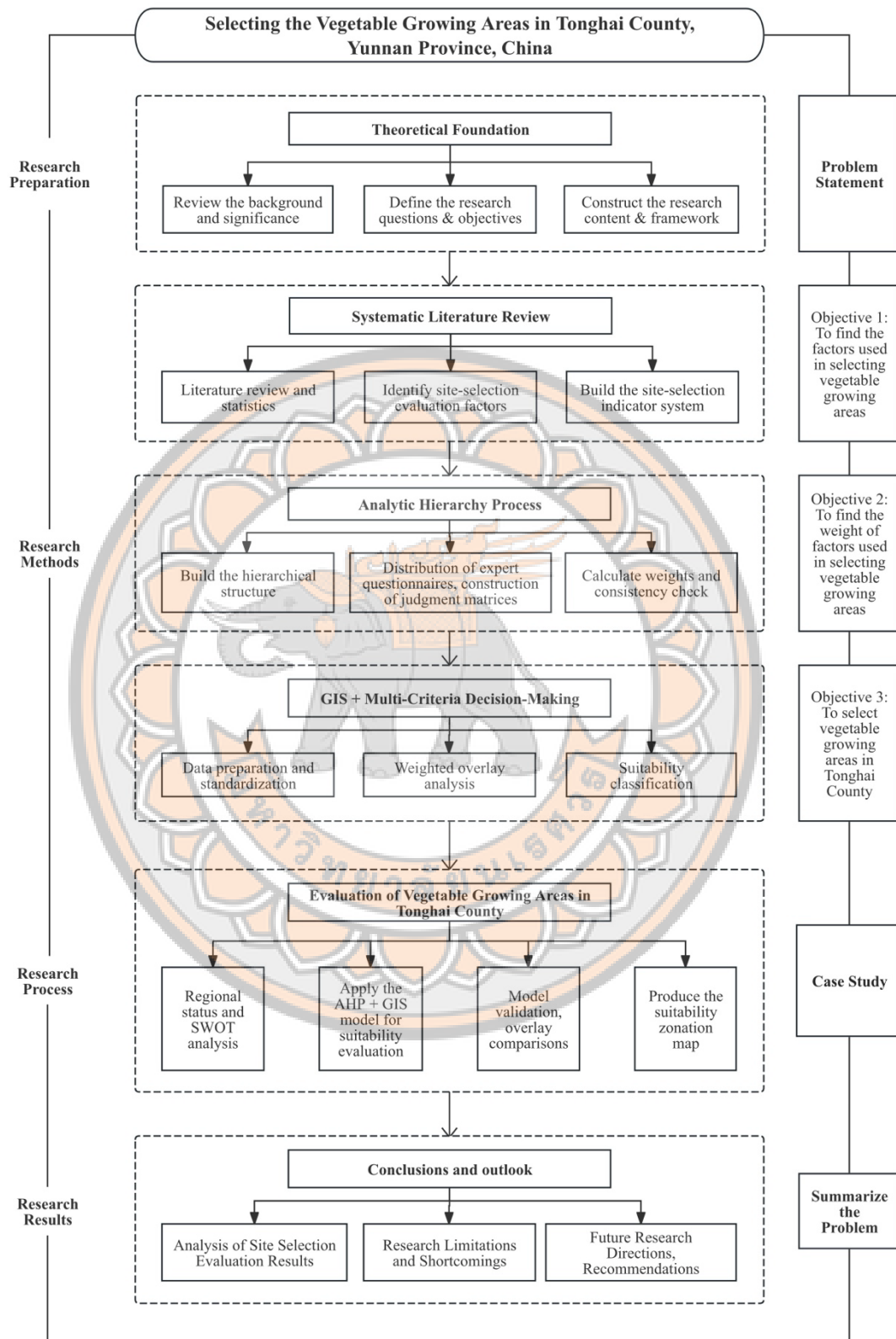


Figure 2 Research Technical Flowchart

3.2 Development of Evaluation Indicator System Based on Literature Review Method

3.2.1 Method Overview

The literature review method is a systematic approach for identifying, selecting, and critically evaluating existing research (Snyder, 2019). In this study, it aims to construct a scientific, comprehensive, and operational evaluation indicator system by thoroughly reviewing domestic and international academic literature related to agricultural land suitability and crop site selection. This phase corresponds to the first specific objective of the research: identifying factors for selecting vegetable growing areas. The theoretical basis, screening process, and overall evidence-synthesis results of the SLR are presented in Section 2.5, while the following sections explain how the literature evidence was incorporated into the evaluation indicator system.

3.2.2 Evaluation Indicator Source Selection

To ensure the framework balances universality with local adaptability, indicator sources employ a "dual evidence chain": authoritative evaluation systems (Group S) and sample literature (Group L).

1) Authoritative Evaluation Framework (Group S)

To avoid reliance solely on case-based evidence, this study first compiles authoritative frameworks related to land suitability, agricultural land evaluation, ecological constraints, and rural infrastructure, forming the Group S inventory (labeled S1 –S8), as summarized in Table 2.

Table 2 Authoritative Evaluation Systems

No	Issuing Authority	System Name	Primary Indicator
S1	FAO	A Framework for Land Evaluation (1976)	Land Characteristics Topography/Soil/Irrigation/ Climate Limiting Factors and Suitability Grades

No	Issuing Authority	System Name	Primary Indicator
S2	FAO & IIASA	GAEZ v4 Methodology (2022)	Caloric/Moisture Matching Soil and Topography Management Scenarios Ecological Constraint Level
S3	USDA-NRCS	Land Capability / Soil Taxonomy	Land Capability Grading Slope and Erosion Water Retention and Mechanical Feasibility
S4	Ministry of Natural Resources (China)	Land Use Control/Permanent Basic Farmland Standards	Basic Farmland Ecological Conservation Red Line Hard Constraint Boundaries
S5	FAO	Guidelines for Land Evaluation for Irrigated Agriculture	Water Availability Irrigation reliability rate Salinization Risk
S6	WHO/UNEP	Principles for Drinking Water Source Protection Areas	Water Source Classification and Buffer Areas (Constraint-Based Approach)
S7	USDA/ARS Academic Review	Effects of Extreme Temperatures on Crops	Effects of High Temperature/Extreme Temperature Thresholds on Growth Processes
S8	Esri (Technical Specifications)	Network Analyst/Cost Distance	Network Travel Time and Cost Distance Model Supports Time-Cost Calculations for "To Trunk Lines/Markets/Cold Chain"

2) Literature Evidence (Group L)

To avoid direct replication, this study primarily searched authoritative databases including Web of Science, Scopus, ScienceDirect, SpringerLink, and MDPI/Frontiers. The search scope covered 2004–2025, supplemented by snowball sampling to expand references (Snyder, 2019). It incorporated empirical research and methodological papers related to "vegetable site selection," "agricultural land suitability," "GIS AHP," "multi-criteria decision-making," and "land evaluation."

In addition to the formal SLR presented in Section 2.5, 16 representative methodological and application references and related policy or technical sources were retained and coded as L1–L16 to support direct tracing of indicator definitions and operational methods (Malczewski, 2006; Ran & Chen, 2023). These coded references do not represent the total number of studies included in the formal SLR. The core references are summarized in Table 3.

Table 3 Summary of Core Literature and Methodological References

No	Author	Research Content
L1	Malczewski (2004)	GIS-MCDM Land Suitability Review, Proposed Process and Key Components (Review Framework)
L2	Malczewski (2006)	GIS-MCDA Review, Trade-offs and Limitations of WLC/OWA Methods
L3	Eastman (1999)	GIS multi-criteria Evaluation: Technical Approach Involving Reclassification, Standardization, and Weighted Overlay
L4	Feizizadeh & Blaschke (2013)	County-Level Agricultural Suitability: A Generalized Paradigm of Boolean Constraints + AHP-WLC
L5	Pramanik (2016)	Empirical Study on AHP-GIS Farmland Suitability: Weighting, Consistency Testing and Rasterization Process

No	Author	Research Content
L6	Hatfield & Prueger (2015)	Effects of Extreme Temperatures on Crop Growth
L7	Oldfield et al. (2019/2022)	Global Meta-Analysis of Soil Organic Matter and Yield
L8	Reeves (1997)	Contribution of Organic Matter to Soil Quality and Productivity
L9	Zolekar & Bhagat (2015)	Hill Farming: The Role of Slope and Accessibility in Suitability
L10	Aung & Chang (2014)	Fresh Produce Supply Chain Temperature/Time Management
L11	Wang et al. (2018)	China's Cold Chain Development and Loss Issues
L12	Esri	Network Analyst / OD Cost Matrix and Cost Distance
L13	FAO & IIASA (2022)	GAEZ Methodology
L14	Han et al. (2021)	PyLUSAT Tool and County-Level Suitability Implementation
L15	Xue et al. (2023)	Practical Application of County-Level Agricultural Suitability
L16	Eastman	Classic Chapter as Implementation Detail Supplement

3.2.3 Evaluation Indicator Identification

Based on the S and L dual evidence repository and considering data availability and practical decision-making needs in Tonghai County, a four-dimensional "primary-secondary indicator-source" inventory was established. Each entry is annotated with attribute types (Benefit Criterion/Cost Criterion/interval-type/constraint-type) to directly interface with GIS reclassification and AHP–WLC operations (Eastman, 2012; Malczewski, 2006).

1) Natural Factor Layer

Natural conditions form the foundation for vegetable growing. At the county level, the interplay of topography, climate, and soil collectively determines whether stable, high-yield, and low-risk growing is feasible. Literature reviews indicate that slope reflects operational difficulty and erosion risk; temperature delineates crops' thermal suitability ranges and heat stress thresholds; soil organic matter reflects fertility and water retention capacity (FAO, 1976; Hatfield & Prueger, 2015; Zolekar & Bhagat, 2015). To avoid collinearity, this study uses annual mean temperature to represent thermal conditions, omitting separate listings for elevation or precipitation.

Evaluation Indicators:

Slope: Steeper slopes increase mechanization difficulty and erosion risk (FAO, 1976; Zolekar & Bhagat, 2015).

Annual mean temperature: Yields are more stable within the suitable range, avoiding the impact of extreme heat (Hatfield & Prueger, 2015).

Soil organic matter: Positively correlated with soil quality and yield.

The natural factor indicators and their corresponding sources are summarized in Table 4.

Table 4 Natural Factor Layer Indicators

Primary Indicators	Secondary Indicators	Attribute	Indicator Source
Natural	Slope (°)	Cost Criterion	S1, S3, L9
Natural	Annual Average Temperature (°C)	Interval Criterion	S2, L6, L13
Natural	Soil Organic Matter (g/kg or SOC%)	Benefit Criterion	L7, L8

2) Economic Factor Layer

Vegetables are highly perishable and heavily reliant on cold chains. Under identical production conditions, the speed of transportation and the ability to

perform timely pre-cooling directly impact arrival quality and loss rates (Aung & Chang, 2014; Wang et al., 2018) (Aung & Chang, 2014). Therefore, this study employs road network travel time rather than straight-line distance to measure efficiency in accessing trunk lines, consolidation and trading, cold chain processing, and connecting to core export markets.

Evaluation Indicators:

Travel time to expressways/national/provincial highways: Reflects efficiency in accessing the rapid road network.

Travel time to county-level wholesale/logistics hubs: Correlates with collection speed and transaction frequency (Aung & Chang, 2014).

Travel time to cold storage/pre-cooling/processing points: Determines "first-hour" cooling and loss control.

Travel time to core export markets: Measures outbound delivery timeliness and arrival quality (Aung & Chang, 2014).

The economic factor indicators and their corresponding sources are summarized in Table 5.

Table 5 Economic Factor Layer Indicators

Primary Indicators	Secondary Indicators	Attribute	Indicator Source
	Travel Time to		
Economic	Expressway/National/Provincial Highway (min)	Cost Criterion	S8, L12
Economy	Travel time to county-level wholesale/logistics hub (min)	Cost Criterion	S8, L12
Economy	Travel time to cold storage/pre-cooling/processing points (min)	Cost Criterion	S8, L11, L12
Economy	Travel time to core export markets (min)	Cost Criterion	S8, L10, L12

3) Social Factors Layer

Effective production requires coordination between "people" and "services." Local agricultural labor influences the scale of organizational operations and daily management, while accessibility to public services impacts the efficiency of technical guidance, financial support, and factor acquisition (Xue et al., 2023).

Evaluation Indicators:

Agricultural labor density/employment ratio: Greater labor availability facilitates organizational development and service integration.

Rural Public Service Accessibility: Average travel time to town government offices/agricultural extension stations/credit outlets (based on facility location and road network analysis).

The social factor indicators and their corresponding sources are summarized in Table 6.

Table 6 Social Factor Layer Indicators

Primary Indicators	Secondary Indicators	Attribute	Indicator Source
social	Agricultural Labor Density/Employment Ratio (%)	Benefit Criterion	Local Statistical Yearbook, L15
social	Rural Public Service Accessibility (min)	Cost Criterion	Local Government Facility Locations, S8

4) Ecological Factor Layer

Ecological and policy boundaries represent baseline requirements and should be vetoed outright. According to national regulations, ecological protection red lines, drinking water source protection areas, and permanent basic farmland shall not be designated as construction land for vegetable bases. In GIS, these areas are directly excluded using Boolean masks (0,1).

Evaluation Indicators:

Ecological Conservation Redlines/Nature Reserves: Follow Ministry of Ecology and Environment guidelines.

Drinking Water Source Protection Areas and Buffer Areas: Aligned with WHO/UNEP principles.

Permanent Basic Farmland: Refer to the Ministry of Natural Resources' criteria.

The ecological constraint factors and their corresponding sources are summarized in Table 7.

Table 7 Ecological Factor Layer Indicators

Primary Indicators	Secondary Indicators	Attribute	Indicator Source
Ecological	Ecological Conservation Redlines/Nature Reserves	Constraint Criterion	S4
Ecological	Drinking Water Source Protection Areas and Buffer Areas	Constraint Criterion	S6
Ecological	Permanent Basic Farmland	Constraint Criterion	S4

Based on the inductive results and referencing the classic classification by (Merino-Benítez et al., 2023) in agricultural land suitability evaluation, the 12 factors were categorized into four criterion layers (natural, economic, social, ecological). The attributes of each indicator layer (Benefit Criterion, Cost Criterion, interval-type, constraint-type) were defined, thereby establishing the evaluation indicator system for selecting vegetable growing sites in Tonghai County.

In addition to the coded core references (L1–L16), the formal SLR presented in Section 2.5 provided broader empirical evidence for the retained indicators. Among the 45 included full-text studies, slope was supported by 19 studies, while annual average temperature and soil organic matter were each supported by 7 studies.

For the economic and supply-chain indicators, travel time to main roads was supported by 5 studies, travel time to county-level wholesale or logistics hubs by 7 studies, travel time to cold-storage/pre-cooling/processing points by 6 studies, and travel time to core export markets by 9 studies. Agricultural labor density or agricultural employment ratio was supported by 4 studies. Rural public service accessibility received no direct support from the included full-text studies but was retained because of its local applicability and spatial measurability. The SLR and policy review also supported the separate consideration of ecological and policy constraints. These literature frequencies were used as descriptive evidence for indicator identification rather than as numerical weights, which were subsequently determined through AHP. Based on the combined evidence from the authoritative frameworks, coded core references, formal SLR, and local applicability, the final evaluation indicator system is presented in Table 8.

Table 8 Evaluation Indicator System for Vegetable Growing Site

Objective Layer	Criterion Layer	Indicator Layer	Attribute	Indicator Source
Site Selection for Vegetable Growing Areas	Natural	Slope (°)	Cost Criterion	S1, S3, L9
		Annual Average Temperature (°C)	Interval Criterion	S2, L6, L13
		Soil Organic Matter (g/kg or SOC%)	Benefit Criterion	L7, L8
	Economic	Travel Time to Expressway/National/Provincial Highway (min)	Cost Criterion	S8, L12
		Travel time to county-level wholesale/logistics hub (min)	Cost Criterion	S8, L12

Objective Layer	Criterion Layer	Indicator Layer	Attribute	Indicator Source
		Travel time to cold storage/pre-cooling/processing points (min)	Cost Criterion	S8, L11, L12
		Travel time to core export markets (min)	Cost Criterion	S8, L10, L12
	social	Agricultural Labor Density/Employment Ratio (%)	Benefit Criterion	Local Statistical Yearbook, L15
		Rural Public Service Accessibility (min)	Cost Criterion	Local Government Facility Locations, S8
		Ecological Conservation Redlines/Nature Reserves	Constraint Criterion	S4
		Drinking Water Source Protection Areas and Buffer Areas	Constraint Criterion	S6
Ecological		Permanent Basic Farmland	Constraint Criterion	S4

3.3 Determination of Evaluation Factor Weights Based on the Analytic Hierarchy Process

3.3.1 Method Overview

The Analytic Hierarchy Process (AHP) is a classical multi-criteria decision-making method that decomposes complex decision problems into hierarchical levels such as objectives, criteria, and alternatives, enabling both qualitative and quantitative analysis (Saaty, 2008). Given that agricultural suitability studies involve multiple dimensions such as natural conditions, economic and transportation factors, social elements, and policy constraints, AHP is widely applied in agricultural site selection and land evaluation research due to its structured and transparent advantages (Mishra, 2015).

This study employs AHP to address the second research objective: determining the weights of factors for selecting vegetable growing areas. Its core advantage lies in quantifying decision-makers' (experts') subjective judgments through pairwise comparisons while effectively testing the logical consistency of these judgments.

AHP was selected for this study because it provides a structured approach for comparing heterogeneous site-selection factors, converting expert judgments into quantitative weights, and testing the logical consistency of those judgments before the weights are incorporated into the GIS analysis.

3.3.2 Operational Procedures

1) Constructing the Hierarchical Model

Based on the evaluation indicator system established in Table 8, this study constructed an AHP hierarchical model for Tonghai County's vegetable growing areas. The model comprises three levels: the objective level, the criterion level, and the indicator level. The objective layer (A) is "Site Selection for Vegetable Growing Areas in Tonghai County"; The criterion layer (B) includes four criteria: natural (B1), economic (B2), social (B3), and ecological (B4), with B4 treated as a constraint criterion rather than an AHP-weighted criterion; the indicator layer (C) comprises 12 specific evaluation indicators, such as slope (C1) and annual average temperature (C2). The resulting AHP hierarchical structure is shown in Figure 3.

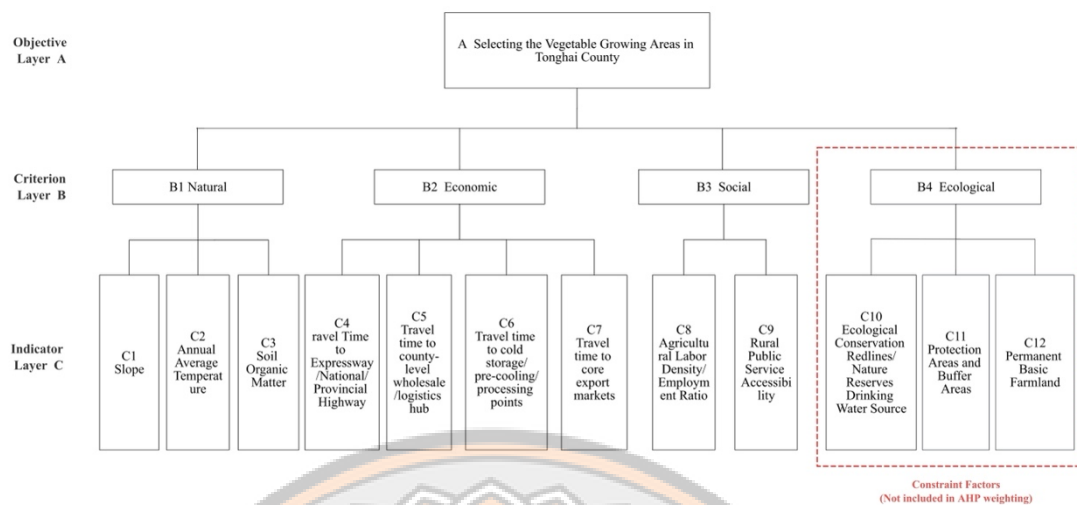


Figure 3 AHP Hierarchical Model for Tonghai County Vegetable Growing Areas

Note: B1–B3 and C1–C9 are scoring factors included in the AHP pairwise comparison and weight calculation. B4 and C10–C12 are constraint factors and are not included in the AHP pairwise comparison or weight calculation; they are considered separately during the GIS-based constraint analysis.

2) Construction of the Judgment Matrix

Following the selection of evaluation factors described earlier, the established evaluation framework was validated through expert surveys. Opinions were gathered from the expert panel via questionnaires, where pairwise comparisons were conducted to score the importance of each influencing factor. This process created a judgment matrix, and the consistency of the matrix was subsequently verified.

In the AHP model of this study, ecological factors constitute strong constraints with non-compensatory characteristics. Therefore, these indicators are not incorporated into the construction of the AHP judgment matrix and weight calculations. Instead, they are processed as constraint layers during the GIS spatial analysis phase.

a. Expert Composition

The judgment matrix of the AHP relies entirely on expert opinions, so the composition of the expert panel directly impacts the scientific validity and credibility of the weightings. To ensure the rigor of the evaluation process and the

objectivity of the results, the construction of this study's expert panel primarily adheres to the following three core criteria:

First, comprehensive coverage of professional domains. To comprehensively weigh the multidimensional complex factors influencing vegetable cultivation site selection—including natural environment, socioeconomic conditions, and policy constraints—the expert pool must encompass all relevant core disciplines: agricultural science, resource and environmental studies, land use planning, and logistics geography.

Second, authoritative expertise credentials. All invited experts must meet at least one of the following criteria: hold an associate senior or higher professional technical title in the relevant field; possess over ten years of relevant research or practical experience; or have participated as a core member in relevant planning or policy formulation at the county level or above. This ensures their judgments are grounded in sufficient professional depth and practical experience.

Third, representative regional knowledge. To balance the universality of evaluation with local particularities, the expert composition must integrate “external perspectives” with “internal knowledge.” This requires including both researchers from academic institutions with macro-regional insights and local administrators and technical personnel deeply familiar with regional realities.

Based on these criteria and referencing (Bozdağ, 2016) recommendation for an ideal panel size of 7 to 11 members, this study ultimately formed a multidisciplinary evaluation team comprising 9 experts. The specific composition is as follows:

Agricultural Growing Experts (2 positions): Capable of evaluating the impact of various natural environmental factors on vegetable growing potential (Tolche, 2022) .

Soil and Water Resources Experts (2 positions): Familiar with soil texture, hydrogeology, and irrigation conditions, capable of determining the importance of soil and water conditions for suitability (Han et al., 2021a).

Land Use and Planning Experts (2 positions): Knowledgeable about land use policies, ecological red lines, and the permanent basic farmland system,

ensuring the evaluation framework aligns with national policy directives (Liu et al., 2018).

Logistics and Supply Chain Experts (2 positions): Capable of evaluating supply chain factors based on market accessibility, cold chain connectivity, and transportation timeliness (Liu et al., 2018).

Local Agricultural Administrator (1 positions): Familiar with Tonghai County's agricultural production and market circulation realities, ensuring expert judgments align with local practices (Ran & Chen, 2023).

The involvement of multidisciplinary experts enables balanced consideration of natural, economic, social, and ecology factors, avoiding overly one-sided research outcomes.

b. Pairwise Comparison

In the weight calculation process, pairwise comparison matrices were constructed for indicators within the same hierarchical level. To reduce potential misunderstanding among experts, the questionnaire provided clear examples. For instance, within the accessibility and Economic Layer, if “travel time to core export markets” is considered more important than “travel time to cold-storage nodes,” a score of 5 can be assigned; if both are equally important, a score of 1 should be used. This approach enables experts to express their judgments on a unified 1-9 scale, reflecting the relative importance and ensuring consistency in evaluation.

Scale Standardization: Employing Saaty's 1-9 scale method, where 1 indicates equal importance, 3 denotes slightly more important, 5 signifies markedly more important, 7 represents strongly more important, and 9 denotes extremely more important; intermediate even numbers serve as transitional values. The definitions of the 1-9 comparison scale used in this study are summarized in Table 9.

Table 9 AHP Judgment Matrix 1-9 Scale Definition Table

Scale Value	Definition	Interpretation
1	Equally important	Two factors have the same impact on the objective
3	Slightly More Important	Factor A is slightly more important than Factor B
5	Strongly important	Factor A is significantly more important than Factor B
7	Extremely important	Factor A is significantly more important than Factor B (as proven by practical experience)
9	Absolutely critical	Factor A is more important than Factor B (proven by factual evidence)
2, 4, 6, 8	Intermediate Value	Used for adjacent judgments (e.g., 2 lies between equal and slightly)
Inverse	Assign reciprocal values	If A is 5 times more important than B, then B is 1/5 as important as A

Based on this scale, the judgment matrices for the criteria layer and the natural, economic, and social indicator layers are presented in Tables 10–13.

Table 10 AHP Judgment Matrix for Each Layer of the Vegetable Growing Areas in Tonghai County (Criteria Layer Judgment Matrix)

Indicator	Natural	Economic	Social
Natural			
Economic			
Social			

Table 11 AHP Judgment Matrix for Each Layer of the Vegetable Growing Areas in Tonghai County (Indicator Layer Judgment Matrix (Natural))

Indicator	Slope (°)	Annual Average Temperature (°C)	Soil Organic Matter (g/kg or SOC%)
Slope (°)			
Annual Average Temperature (°C)			
Soil Organic Matter (g/kg or SOC%)			

Table 12 AHP Judgment Matrix for Each Layer of the Vegetable Growing Areas in Tonghai County (Indicator Layer Judgment Matrix (Economic))

Indicator	Travel Time to Expressway/ National/Pro vincial Highway (min)	Travel time to county- level wholesale/log istics hub (min)	Travel time to cold storage/pre- cooling/processi ng points (min)	Travel time to cold storage/pre- cooling/proce ssing points (min)
Travel Time to Expressway/Nat ional/Provincial Highway (min)				
Travel time to county-level wholesale/logisti cs hub (min)				
Travel time to cold storage/pre- cooling/processi ng points (min)				
Travel time to core export markets (min)				

Table 13 AHP Judgment Matrix for Each Layer of the Vegetable Growing Areas in Tonghai County (Indicator Layer Judgment Matrix (Social))

Indicator	Agricultural Labor Density/Employment Ratio (%)	Rural Public Service Accessibility (min)
Agricultural Labor Density/Employment Ratio (%)		
Rural Public Service Accessibility (min)		

c. Aggregation of Expert Opinions

Since experts come from different fields, differences in opinions are inevitable. Using a single expert's judgment directly may lead to biased weighting results toward a particular discipline. Therefore, this study employs the AIJ (Aggregate Individual Judgments) geometric mean method to aggregate all experts' judgments into a collective judgment matrix (Dong et al., 2010). This approach effectively integrates diverse expert opinions and enhances the objectivity and stability of the final AHP weights.

For each element a_{ij} , the aggregated group value is calculated as:

Formula 3-1 Aggregate Individual Judgments (AIJ)

$$a_{ij}^{(group)} = (\prod_{k=1}^m a_{ij}^{(k)})^{1/m} \quad (3-1)$$

where m denotes the number of experts. The resulting aggregated matrix $A^{(group)} = [a_{ij}^{(group)}]$ is then used to compute the final weight vector and Consistency Ratio (CR). For weight derivation, the geometric mean of each row of the aggregated judgment matrix was calculated and then normalized by the sum of all row geometric means. The normalized values represent the priority weights of the factors

within the corresponding judgment matrix and sum to 1. This procedure was applied to the criteria-layer matrix and each indicator-layer matrix to obtain the criteria weights and local indicator weights, respectively. This procedure reduces subjectivity and preserves the collective knowledge of multidisciplinary experts (Dong et al., 2010; Forman, 1996).

d. Consistency Test

To identify and eliminate logical contradictions in expert judgments—such as situations where "Factor A is superior to Factor B, Factor B is superior to Factor C, yet Factor C is superior to Factor A"—a consistency test must be performed on the aggregated judgment matrix.

First, calculate the Consistency Index (CI) using the formula.

Formula 3-2 Consistency Index (CI)

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (3-2)$$

Where:

$\lambda_{\max}$ is the largest eigenvalue of the judgment matrix.

n is the order of the judgment matrix (i.e., the number of factors at the same level).

Subsequently, the consistency ratio (CR) is calculated using the formula.

Formula 3-3 Consistency Ratio (CR)

$$CR = \frac{CI}{RI} \quad (3-3)$$

Where:

CI denotes the consistency index.

RI denotes the Random Consistency Index, whose value depends on the order n of the matrix and can be obtained from a table. The RI values corresponding to different matrix orders are provided in Table 14.

The acceptance criterion is when $CR < 0.10$, the consistency of the judgment matrix is considered acceptable; if $CR \geq 0.10$, the consistency fails and requires revision until the requirement is met (Ishizaka & Labib, 2011).

Table 14 Random Consistency Index (RI) Reference Table

Matrix order n	1	2	3	4	5	6	7	8	9	10	11	12
RI value	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48

3.3.3 Output Results

Through the above steps, this study ultimately obtained:

- 1) Expert judgments that passed consistency testing, ensuring the rationality and logical coherence of weight allocation.
- 2) Weight sets for each evaluation factor, including weights of the criterion layer relative to the objective layer and weights of the indicator layer relative to its criterion layer, ultimately yielding the comprehensive weight of each indicator layer relative to the overall objective.

These weights will be integrated with spatial data in the GIS platform to form a weighted linear combination (WLC) model, providing the foundation for evaluating site selection for vegetable growing areas in Tonghai County (Xue et al., 2023). The weighting factors and their hierarchical relationships used in the site-selection evaluation are summarized in Table 15.

Table 15 Weighting Factors for Site Selection Evaluation of Vegetable Growing Areas in Tonghai County

Objective Layer	Criterion Layer	Criterion Layer Weight	Indicator Layer	Indicator layer weights	Weight of Indicator Layer on Overall Objective Layer
Site Selection for Vegetable Growing Areas	Natural		Slope (°)		
			Annual Average Temperature (°C)		
			Soil Organic Matter (g/kg or SOC%)		
			Travel Time to Expressway/National/Provincial Highway (min)		
	Economic		Travel time to county-level wholesale/logistics hub (min)		
			Travel time to cold storage/pre-cooling/processing points (min)		
			Travel time to core export markets (min)		
	Social		Agricultural Labor		

Objective Layer	Criterion Layer	Criterion Layer Weight	Indicator Layer	Indicator layer weights	Weight of Indicator Layer on Overall Objective Layer
			Density/Employment Ratio (%)		
			Rural Public Service Accessibility (min)		
			Ecological Conservation Redlines/Nature Reserves	-	-
Ecological		-	Drinking Water Source Protection Areas and Buffer Areas	-	-
			Permanent Basic Farmland	-	-

3.4 Suitability Evaluation Based on GIS and Multi-Criteria Decision Making

3.4.1 Method Overview

In this study, Geographic Information System (GIS) serves as the key technological tool for translating conceptual evaluation methods into spatial outcomes. GIS not only integrates and manages multi-source geographic data but also converts factors such as natural, social, and supply chain elements into visualized suitability distribution results through spatial analysis methods (Malczewski, 2006). When combined with weighting results from the Analytic Hierarchy Process (AHP), GIS provides computable, interpretable, and reproducible solutions for complex multi-

criteria decision-making problems(Feizizadeh & Blaschke, 2013). The integration of GIS with multi-criteria decision analysis has proven to be a powerful paradigm for addressing spatial location problems(Malczewski, 2006).

This phase aims to achieve the third core objective of the study: identifying and delineating the optimal vegetable growing areas in Tonghai County. The technical principle involves systematically integrating factor weights obtained from AHP with spatial data layers in GIS. Through Weighted Overlay Analysis, this process ultimately generates a spatial suitability zoning map. This method efficiently processes massive spatial information and quantifies multi-criteria decision-making into unified evaluation standards, significantly enhancing the scientific rigor and transparency of the site selection process(Eastman, 2012).

3.4.2 Operational Steps

1) Spatial Data Preparation

All spatial data used in this study will be sourced from public platforms, primarily including the Resource and Environmental Science Data Center (RESDC) of the Chinese Academy of Sciences, the U.S. Geological Survey (USGS) Earth Explorer platform, and OpenStreetMap (OSM).

The core dataset includes Tonghai County administrative boundaries, digital elevation models (DEM), soil type distribution maps, road and river vector data, and current land use maps.

All data will undergo preprocessing within the ArcGIS Pro software platform. Specific steps included unifying the projection coordinate system, clipping data to the study area boundaries, and resampling all raster data to a uniform 30-meter spatial resolution. This ensured consistent spatial coverage and accuracy across all data layers.

2) Single-factor suitability assessment and normalization

Due to differences in units and numerical ranges among evaluation factors (e.g., slope measured in degrees, distance in meters), all factor layers must be uniformly normalized to a dimensionless suitability score range before spatial overlay. This study employed a 1-5 rating system for recategorization, where 5 indicates highly suitable and 1 indicates extremely unsuitable.

Within GIS, differentiated standardization methods were applied based on the attribute characteristics of each factor.

Cost-type factors are more suitable with smaller values, categorized into 1–5 levels using equidistant intervals, natural breaks, or literature-based methods.

Benefit-type factors are more suitable at higher values, with scoring following the reverse order of cost-type factors.

Interval-type factors have an optimal range. Assign the highest score of 5 to this optimal range, then assign decreasing scores based on deviation from this range.

Constraint factors employ Boolean logic to create binary mask layers, where suitable development areas are assigned a value of 1, while prohibited development areas are assigned a value of 0 or set to No Data.

3) Weighted Overlay Analysis

This step constitutes the core of the MCDM model. Utilizing the Weighted Sum Tool in GIS, all reclassified scoring factor layers serve as inputs. The composite weights derived from AHP (indicating each indicator layer's relative importance to the overall objective) function as weighting coefficients for the overlay calculation. This yields suitability scores, where each pixel's final value represents the weighted sum of its normalized factor values and respective weights.

This method allows for a certain degree of compensatory relationships among different factors. That is, when the suitability of one factor is relatively low, the higher suitability of other factors can partially compensate for its deficiency, thereby better aligning with the comprehensive characteristics of agricultural site selection.

Formula 3-4 Weighted Overlay Analysis

$$S = \sum_{i=1}^n (w_i \times x_i) \quad (3-4)$$

Where:

S represents the final comprehensive suitability score for each grid cell.

w_i represents the comprehensive weight of the factor (must satisfy $\sum_{i=1}^n w_i = 1$).

X_i represents the standardized suitability score (1 –5) for the i -th factor.

n denotes the total number of factors involved in the overlay.

4) Constraint Masking

After obtaining suitability scores, this study further incorporates constraint masks to enforce hard constraints such as policy boundaries and ecological redlines. Based on the attribute characteristics of each factor, the scoring factors are normalized in GIS using differentiation, and the constraint-based factors use Boolean logic to generate binary masks. The mask layer is expressed in binary form, assigning values of 1 to usable areas and 0 to prohibited areas.

By performing raster-by-raster multiplication of the composite suitability grid with the mask in GIS, all prohibited areas are strictly excluded from the results. This process effectively guarantees the compliance and policy alignment of the research results (Jiang, 2007).

Formula 3-5 Constraint Masking

$$S^* = S \times M \quad (3-5)$$

Where:

S^* represents the final composite suitability score.

S denotes the suitability score.

M denotes the Boolean constraint mask (1,0).

5) Graded Expression

The output after weighted overlay is a continuous composite suitability score raster layer. To facilitate spatial planning and decision-making, this continuous value needs to be divided into discrete suitability grades. This study employs Jenks' Natural Breaks method for classification. This objective, data-driven approach identifies optimal classification intervals based on the intrinsic distribution characteristics of the data itself, maximizing inter-class variation while minimizing intra-class variation (Jenks, 1967).

The final classification of Tonghai County's vegetable growing sites comprises five tiers: Very High Suitability Area, High Suitability Area, Moderate Suitability Area, Low Suitability Area, Unsuitable Area.

3.4.3 Model Validation and Sensitivity Analysis

To ensure the reliability of evaluation results, this study will employ the "existing cropping pattern validation method" to validate the model (Feizizadeh & Blaschke, 2013).

Validation Data: Vector maps of existing high-yield vegetable growing areas, verified through field surveys, will be obtained from the Tonghai County Bureau of Agriculture and Rural Affairs.

Validation Process: In a GIS environment, overlay analysis will be performed between the existing vegetable growing area vector map and the suitability zoning map generated in this study.

Validation Metric: The percentage of existing vegetable-growing areas falling within the model defined "Very High Suitability" and "High Suitability" areas will be calculated. The resulting proportion will be used to assess the degree of spatial correspondence between the model-derived suitability results and the existing vegetable growing pattern, with a higher proportion indicating stronger spatial consistency.

In addition to model validation, sensitivity analysis will be conducted to further test the robustness of the weighting system used in the AHP–GIS model. The criteria-layer weights will be perturbed by $\pm 10\%$. If the resulting change in the combined High and Very High Suitability area remains limited, the model will be considered relatively robust (Feizizadeh & Blaschke, 2013).

3.4.4 Research Outputs

Based on the above process, the final outputs of this study are:

- 1) A suitability zoning map for vegetable growing areas in Tonghai County, visually illustrating the spatial distribution of different suitability levels.
- 2) County-wide statistics on suitable area by suitability grade.
- 3) Township-level suitability grade statistics tables.
- 4) Supporting legends and explanatory notes. These outputs facilitate spatial pattern analysis in academic research while providing local governments with intuitive references for agricultural planning and land management.

In summary, this chapter systematically constructs a research methodology integrating AHP and GIS for vegetable growing site selection. It encompasses the entire process from indicator development and weight determination to spatial analysis and result validation. This framework ensures systematicity, transparency, and reproducibility throughout the research process, laying a robust methodological foundation for the subsequent empirical study in Tonghai County. This foundation will enable the generation of specific suitability zoning maps and subsequent analysis in the next chapter.



CHAPTER IV

CASE STUDY

4.1 Overview of the Case Study Area

Tonghai County is located in central Yunnan Province. Its topography, climate, soil, and transportation conditions exhibit distinct spatial variation, making the county a representative case for evaluating the suitability of vegetable growing areas at the county scale. From a natural-condition perspective, the central part of the county and the area surrounding Qilu Lake are dominated by lake-basin and flatland landforms, with relatively gentle terrain and intensive agricultural use. Mountainous terrain is widely distributed in the peripheral areas, where slope, elevation, and agricultural production conditions vary substantially. These differences in temperature, soil fertility, and cultivation conditions provide the natural basis for the spatial differentiation of vegetable-growing suitability.

From an industrial perspective, vegetable production in Tonghai County is characterized by large-scale, commercialized, and export-oriented operations. In addition to meeting local demand, a substantial share of vegetable products is supplied to markets within and outside Yunnan Province. Because vegetables are perishable, sensitive to quality loss, and highly dependent on transportation timeliness, the spatial layout of growing areas is influenced not only by slope, temperature, and soil conditions but also by accessibility to roads, wholesale markets, cold-chain facilities, and external markets.

From a spatial decision-making perspective, agricultural production space in Tonghai County must be coordinated with water-environment protection, farmland conservation, and urban-rural development space. Site selection based solely on natural production conditions may produce results that are inconsistent with water-environment protection, farmland-use controls, or supply-chain operating conditions. Territorial spatial-control requirements, including ecological conservation red lines and protected areas, water-environment protection zones, and permanent basic farmland, also affect the practical layout of vegetable growing areas. Because these constraints differ in data availability and regulatory requirements, they were examined separately before the

operational constraint layer was determined. Tonghai County therefore combines a strong vegetable-industry foundation with pronounced natural, locational, and social spatial differences, making it suitable for application of an integrated AHP-GIS evaluation model.

Based on these characteristics, this chapter applies the indicator system and research methods established in the preceding chapters. First, judgment matrices are constructed from the expert questionnaire results and the weights of the evaluation indicators are determined. Second, GIS spatial analysis is used to spatialize, standardize, and score each evaluation factor. Finally, weighted overlay and constraint masking are applied to evaluate the suitability of vegetable growing areas and identify priority locations, thereby providing a basis for optimizing the spatial layout of vegetable production in the study area. The location of the study area is shown in Figure 4.

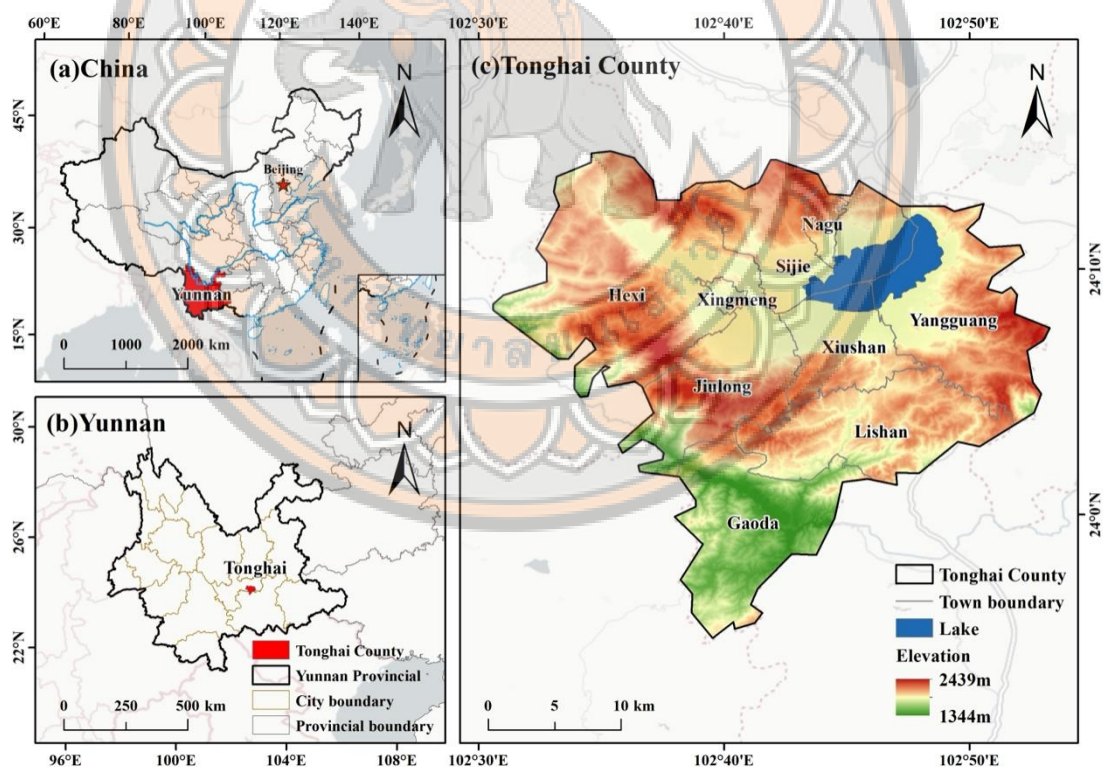


Figure 4 Location of the Study Area in Tonghai County

4.2 Application of the AHP Model and Determination of Indicator Weights

4.2.1 Expert Questionnaire Processing and Construction of Judgment Matrices

To determine the relative importance of the evaluation indicators for selecting vegetable growing areas in Tonghai County, this study used an expert questionnaire to collect pairwise-comparison judgments. The questionnaire covered expert background information, comparisons among criteria-level factors, comparisons among subcriteria, and confirmation of constraint conditions. Its main purpose was to obtain professional judgments regarding the relative importance of each factor and to provide the basic data required for subsequent AHP weight calculation.

Nine experts from relevant fields were invited to participate. All nine questionnaires were returned and considered valid, producing a valid-response rate of 100%. The panel included specialists in crop production, soil and water resources, land use and planning, logistics and supply chain management, and local agricultural administration. Participants came from universities and research institutes, government departments, enterprises, and local agricultural management or technical organizations. Overall, the panel provided a reasonably representative combination of academic knowledge, practical experience, and planning involvement.

Table 16 Summary of Expert Information

Expert Code	Expert Category	Qualification	Organization Type	Years of Experience	County-Level Planning	Familiar with Tonghai
E1	Agricultural planting expert	Associate senior title or above; >10 years	University/research institute	15	Yes	Yes
E2	Agricultural planting expert	>10 years of experience	Enterprise	12	No	Yes
E3	Soil and water resources expert	Associate senior title or above	University/research institute	18	Yes	Yes
E4	Soil and water resources expert	>10 years of experience	Government	11	Yes	Yes
E5	Land use and planning expert	Associate senior title or above	University/research institute	20	Yes	Yes
E6	Land use and planning expert	>10 years of experience	Government	14	Yes	Yes
E7	Logistics and supply chain expert	Associate senior title or above	University/research institute	13	Yes	Yes
E8	Logistics and supply chain expert	>10 years of experience	Enterprise	16	No	Yes
E9	Local agricultural management/technical personnel	>10 years; core participant in county planning	Government	22	Yes	Yes

Each valid questionnaire was converted into a reciprocal judgment matrix using Saaty's 1-9 scale. Before aggregation, the completeness and internal logic of each questionnaire were checked. Missing values, inconsistent reciprocal entries, and responses that did not meet the questionnaire requirements were reviewed. Because all returned questionnaires satisfied the basic quality requirements, all nine were retained

for group aggregation. The background and qualifications of the nine experts are summarized in Table 16.

4.2.2 Construction of Group Judgment Matrices

After the individual judgment matrices were constructed, the judgments of the nine experts were aggregated to form group judgment matrices. The Aggregation of Individual Judgments (AIJ) approach was adopted, and the geometric mean of the corresponding pairwise-comparison values was calculated. This approach preserves the reciprocal property of the judgment matrices while reducing the influence of extreme individual judgments. The aggregated group judgment matrices for the criteria, natural, economic, and social layers are presented in Tables 17–20.

Table 17 Group Judgment Matrix of the Criteria Layer

Criteria	Natural Factors	Economic Factors	Social Factors
Natural Factors	1	1.166529	2.564642
Economic Factors	0.857244	1	2.505293
Social Factors	0.389918	0.399155	1

Table 18 Group Judgment Matrix of Natural Factors

Natural Factor	C1 Slope	C2 Annual Average Temperature	C3 Soil Organic Matter
C1 Slope	1	0.907307	0.466269
C2 Annual Average Temperature	1.102163	1	0.456918
C3 Soil Organic Matter	2.144685	2.188575	1

Table 19 Group Judgment Matrix of Economic Factors

Economic Factor	C4 Main Roads	C5 Wholesale/Logistics Hubs	C6 Cold Storage/Pre-Cooling/Processing	C7 Core Export Markets
C4 Main Roads	1	0.602210	0.568196	0.29133
C5				
Wholesale/Logistics Hubs	1.660552	1	0.925875	0.361015
C6 Cold Storage/Pre-Cooling/Processing	1.759955	1.080059	1	0.431111
C7 Core Export Markets	3.432532	2.769970	2.319588	1

Table 20 Group Judgment Matrix of Social Factors

Social Factor	C8 Agricultural Labor Density	C9 Rural Public Service Accessibility
C8 Agricultural Labor Density	1	1.682484
C9 Rural Public Service Accessibility	0.594360	1

The matrices show that the expert group assigned relatively high importance to natural conditions and supply-chain accessibility. Within the natural-factor matrix, soil organic matter was judged more important than slope and annual average temperature. Within the economic-factor matrix, accessibility to core export markets was assigned the greatest relative importance. These judgments are consistent

with the production characteristics of vegetables and the export-oriented nature of Tonghai County's vegetable industry.

4.2.3 Indicator Weight Calculation Results

Following construction of the group judgment matrices in Tables 17–20, the geometric-mean and normalization procedure described in Section 3.3.2 was applied to obtain the criteria-layer weights and the local weights of the indicators. The overall weight of each indicator was then calculated by multiplying its local weight by the corresponding criteria-layer weight. For example, the overall weight of C1 Slope was calculated as $0.4408 \times 0.2330 = 0.1027$. The final weights of C1–C9 are presented in Table 21.

Table 21 Weights of Suitability Evaluation Indicators for Vegetable Growing Areas in Tonghai County

Criteria Layer	Criteria Weight	Indicator	Local Weight	Overall Weight
Natural Factors	0.4408	C1 Slope	0.2330	0.1027
		C2 Annual Average Temperature	0.2470	0.1089
		C3 Soil Organic Matter	0.5200	0.2292
Economic Factors	0.3946	C4 Travel Time to Main Roads	0.1237	0.0488
		C5 Travel Time to County-Level Wholesale/Logistics Hubs	0.1901	0.0750
		C6 Travel Time to Cold Storage/Pre-Cooling/Processing Points	0.2093	0.0826
		C7 Travel Time to Core Export Markets	0.4770	0.1882
		C8 Agricultural Labor Density	0.6272	0.1032
Social Factors	0.1645	C9 Travel Time to Rural Public Services	0.3728	0.0613

At the criteria level, natural factors received the highest weight, followed by economic and social factors. At the indicator level, soil organic matter had the largest overall weight (0.2292), followed by travel time to core export markets (0.1882). Annual average temperature, agricultural labor density, and slope also received substantial weights. The results indicate that production conditions remain fundamental, while market accessibility and logistics timeliness are also central to the spatial selection of export-oriented vegetable growing areas.

4.2.4 Consistency Test Results

Based on the normalized weight vectors derived from the group judgment matrices, the maximum eigenvalue ($\lambda_{\max}$), consistency index (CI), and consistency ratio (CR) were calculated for each matrix. A matrix was considered acceptable when $CR < 0.10$. The consistency-test results for all group judgment matrices are summarized in Table 22.

Table 22 Consistency Test Results of Judgment Matrices

Judgment Matrix	n	Maximum Eigenvalue ($\lambda_{\max}$)	CI	CR	Result
Criteria Layer	3	3.0019	0.0009	0.0016	Passed
Natural Factors	3	3.0015	0.0008	0.0013	Passed
Economic Factors	4	4.0079	0.0026	0.0029	Passed
Social Factors	2	2.0000	0.0000	0.0000	Passed

All CR values were below 0.10, indicating acceptable consistency. Therefore, the group judgments and derived indicator weights were suitable for subsequent GIS-based weighted overlay analysis.

4.3 GIS Spatial Analysis and Processing of Evaluation Factors

4.3.1 Spatialization of Evaluation Factors

Based on the indicator system established in Chapter 3, the nine evaluation factors were converted into spatial layers for GIS overlay analysis. During model processing, the datasets were assigned a common spatial reference, clipped to the study area, and converted to raster format with a nominal spatial resolution of 30 m. A common analysis extent, cell size, snap raster, and mask were used throughout the raster-processing workflow. The data sources and spatial-processing methods for the nine evaluation factors are summarized in Table 23.

Natural factors were derived from terrain, climate, and soil datasets. Slope was calculated from the DEM; annual average temperature and soil organic matter were clipped and resampled to the study area. Economic and social accessibility factors were generated through road-network analysis using assigned travel speeds for different road classes. The resulting travel-time surfaces represent the estimated shortest network travel time to the relevant road, facility, or market node.

Table 23 Data Sources and Spatial Processing Methods of Evaluation Factors

Indicator	Data Source	Spatial Processing Method
C1 Slope	DEM, Geospatial Data Cloud	Slope calculation; clipping; rasterization
C2 Annual Average Temperature	Resources and Environmental Science and Data Platform	Clipping; resampling; rasterization
C3 Soil Organic Matter	National Tibetan Plateau Data Center	Clipping; resampling; rasterization
C4 Main Road Accessibility	OpenStreetMap road network	Network travel-time analysis
C5 County-Level Wholesale/Logistics Accessibility	OSM roads and Amap POIs	Network travel-time analysis to wholesale/logistics hubs
C6 Cold Storage/Pre-Cooling/Processing Accessibility	OSM roads and Amap POIs	Network travel-time analysis to cold-chain nodes

Indicator	Data Source	Spatial Processing Method
C7 Core Export Market Accessibility	OSM roads and market nodes	Network travel-time analysis
C8 Agricultural Labor Density	Amap village/community/settlement POIs	Point-density calculation
C9 Rural Public Service Accessibility	OSM roads and Amap public-service POIs	Network travel-time analysis

For the road-network analysis, expressways were assigned a travel speed of 90 km/h, main roads 50 km/h, secondary roads 40 km/h, and other roads 30 km/h. These standardized travel speeds were used to create comparable accessibility surfaces. Agricultural labor density was represented by settlement-point density because spatially explicit agricultural labor data were not available. This proxy reflects the spatial concentration of rural population and agricultural activity rather than the exact number of agricultural workers.

4.3.2 Standardization and Scoring of Evaluation Factors

Because C1-C9 differ in data type, measurement unit, and value range, they cannot be directly combined. Each factor was therefore standardized to an integer suitability score ranging from 1 to 5. A score of 5 indicates conditions most favorable for vegetable growing-area selection, whereas a score of 1 indicates relatively unfavorable conditions.

Natural factors were classified according to vegetable production requirements and the observed conditions in Tonghai County. Gentle slopes received higher scores because they facilitate mechanized operations, irrigation infrastructure, and large-scale production. Annual average temperature was treated as an interval-optimum factor, with 15-18 °C defined as the most suitable range. The observed annual average temperature in Tonghai County ranged from 14.842445 to 19.016636 °C; consequently, only scores of 4 and 5 occurred in the standardized C2 raster. Soil organic matter was treated as a positive factor, with higher values receiving higher suitability scores.

Economic accessibility factors and rural public-service accessibility were classified using consistent road-network travel-time thresholds: 0-15 minutes = 5, 15-30 minutes = 4, 30-45 minutes = 3, 45-60 minutes = 2, and more than 60 minutes = 1. Shorter travel times indicate stronger connectivity to transportation routes, markets, cold-chain facilities, and public services. Agricultural labor density was classified using settlement-point density, with higher-density areas assigned higher scores.

Table 24 Standardization and Scoring Criteria of Evaluation Factors

Code	Evaluation Factor	Score 5	Score 4	Score 3	Score 2	Score 1
C1	Slope (°)	$0 \leq X \leq 3$	$3 < X \leq 5$	$5 < X \leq 8$	$8 < X \leq 15$	$15 < X \leq 64.10$
C2	Annual Average Temperature (°C)	$15 \leq T \leq 18$	$14.842445 \leq T < 15$ or $18 < T \leq 19.016636$	-	-	-
C3	Soil Organic Matter (%)	2.327-2.590	2.096-2.327	1.888-2.096	1.591-1.888	1.185-1.591
C4	Travel Time to Main Roads (min)	0-15	15-30	30-45	45-60	>60
C5	Travel Time to County-Level Wholesale/Logistics Hubs (min)	0-15	15-30	30-45	45-60	>60
C6	Travel Time to Cold Storage/Pre-Cooling/Processing Points (min)	0-15	15-30	30-45	45-60	>60
C7	Travel Time to Core Export Markets (min)	0-15	15-30	30-45	45-60	>60
C8	Agricultural Labor Density (settlement points/km ²)	2.537-4.147	1.415-2.537	0.764-1.415	0.325-0.764	0-0.325

Code	Evaluation Factor	Score 5	Score 4	Score 3	Score 2	Score 1
C9	Travel Time to Rural Public Services (min)	0-15	15-30	30-45	45-60	>60

As shown in Table 24, negative, positive, and interval-optimum scoring rules were used according to the direction of each indicator's effect on suitability. After standardization, a higher score consistently indicates a more favorable condition for vegetable growing-area selection. The choice of standardization and classification method can materially affect GIS-based multi-criteria evaluation results; therefore, the scoring rules were selected according to indicator characteristics and the observed data distribution (Radočaj et al., 2020; Yin et al., 2020).

1) Standardization Results for Natural Factors

The standardized suitability distributions of slope, annual average temperature, and soil organic matter are presented in Figures 5 to 7.

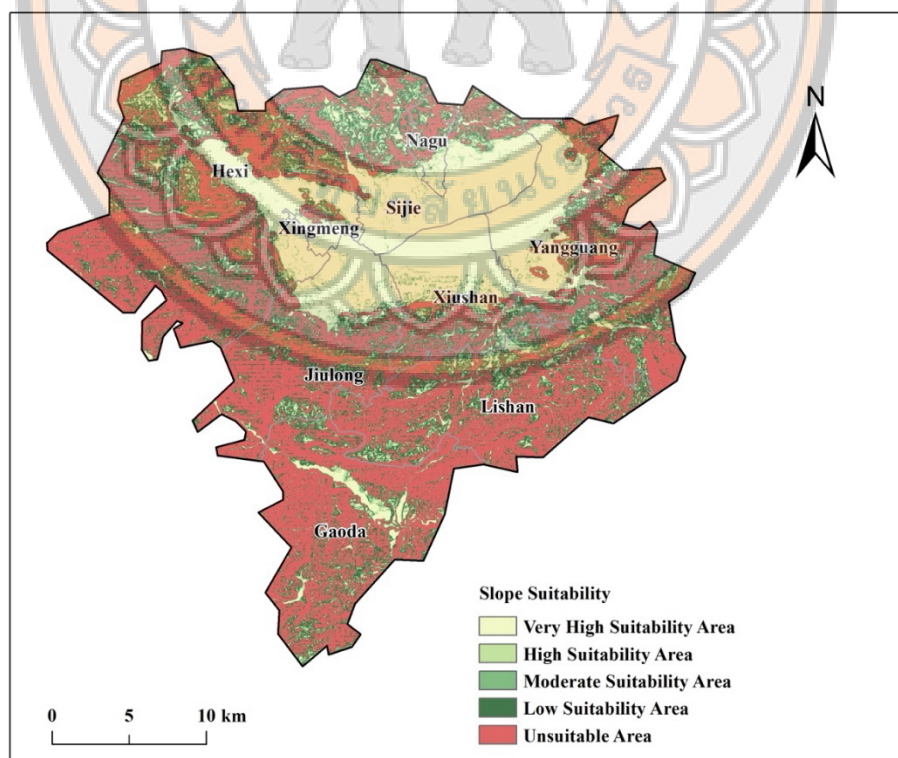


Figure 5 Standardized Slope Suitability Map

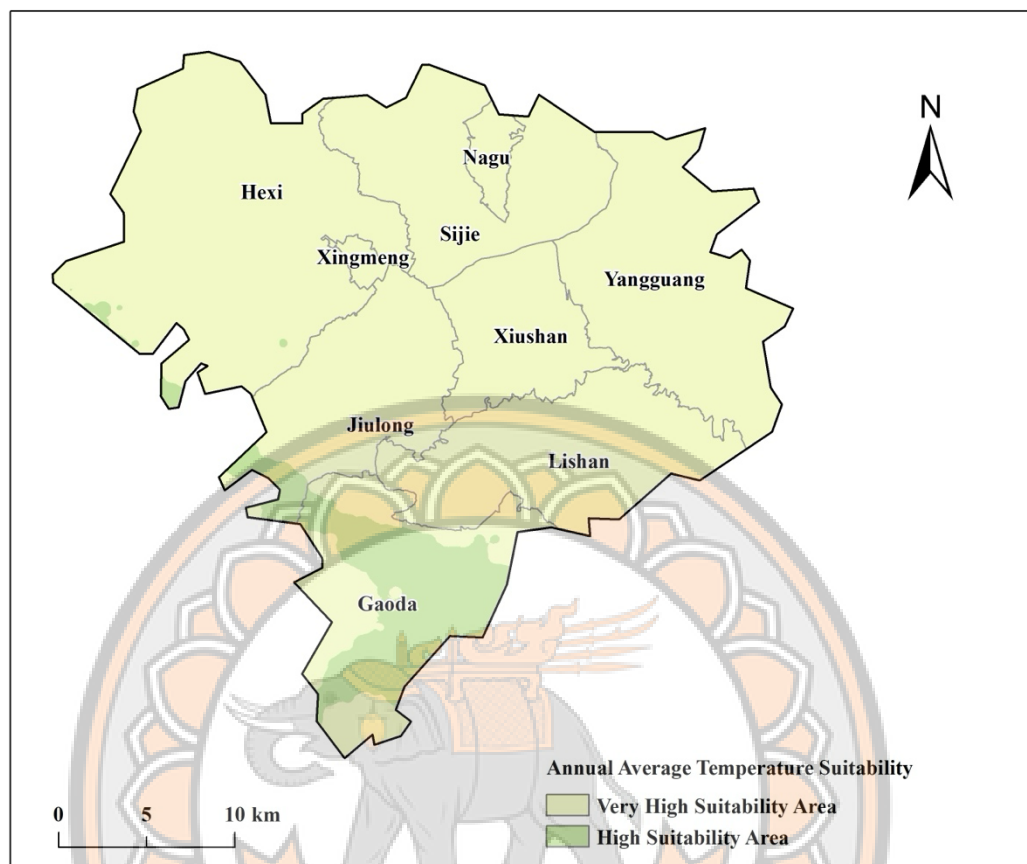


Figure 6 Standardized Annual Average Temperature Suitability Map

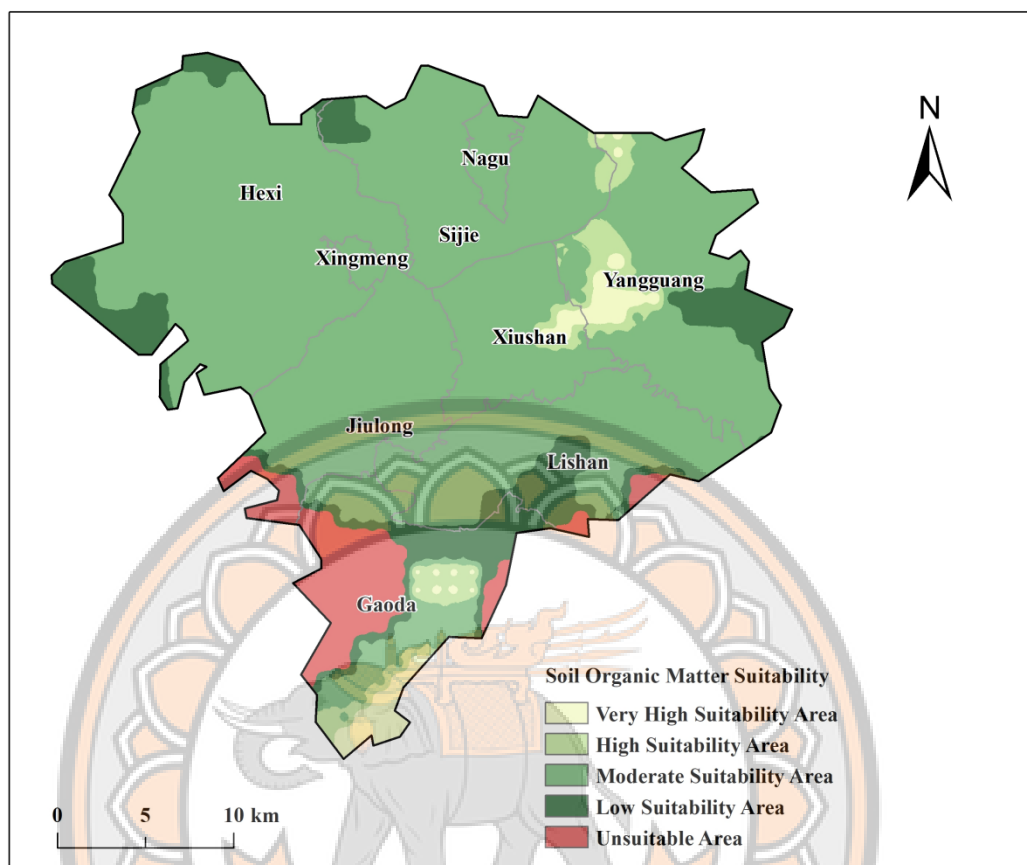


Figure 7 Standardized Soil Organic Matter Suitability Map

The high-scoring slope areas are primarily located in the central lake-basin and flatland zones, including Sijie, Xingmeng, Xiushan, and Yangguang, as well as some relatively flat areas of Hexi and Nagu. Low-scoring and unsuitable slope areas are concentrated in Jiulong, Lishan, Gaoda, and the mountainous western, southern, and eastern peripheries. High annual-temperature suitability covers most of the county, while the relatively lower temperature suitability class is concentrated mainly in Gaoda and parts of the southern area. High-scoring soil organic matter areas occur mainly in eastern Yangguang, the Xiushan-Yangguang transition area, and parts of southern Gaoda; lower-scoring areas are distributed in central-western Gaoda, southern Jiulong, and southeastern Lishan. The three natural factors do not exhibit identical spatial patterns, indicating substantial local differences in terrain, thermal conditions, and soil fertility.

2) Standardization Results for Economic Factors

The standardized accessibility results for main roads, county-level wholesale and logistics hubs, cold-storage/pre-cooling/processing points, and core export markets are shown in Figures 8 to 11.

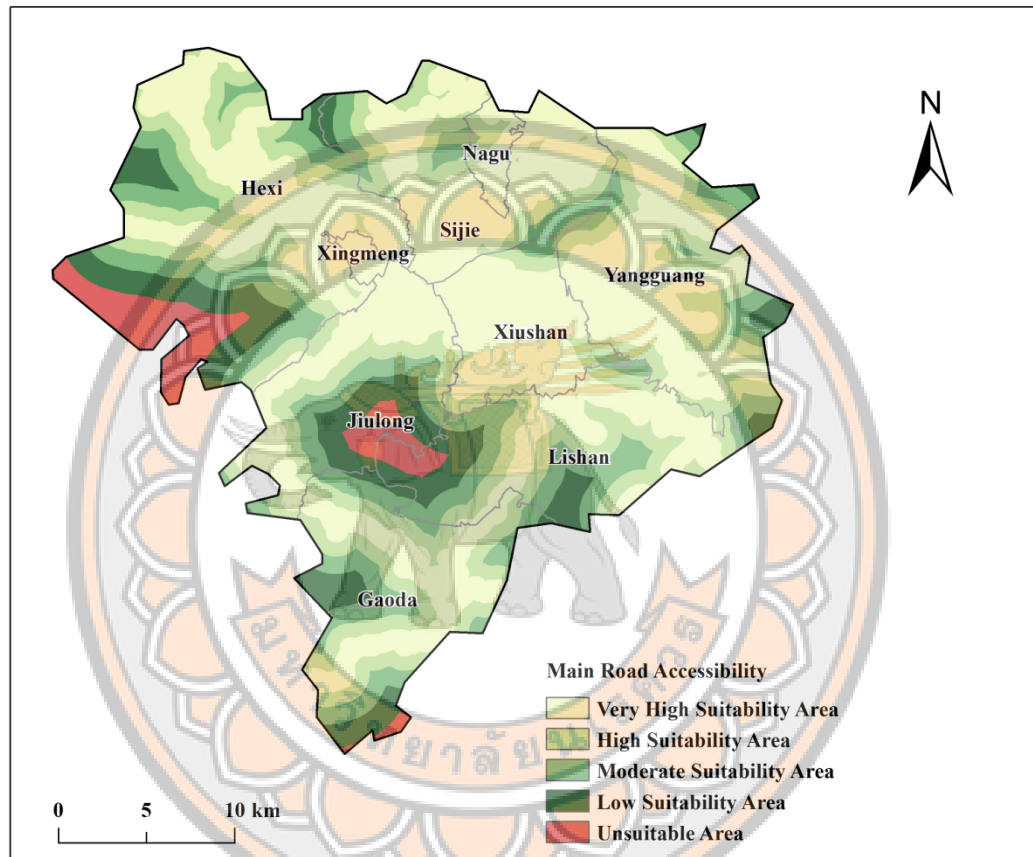


Figure 8 Standardized Main Road Accessibility Map

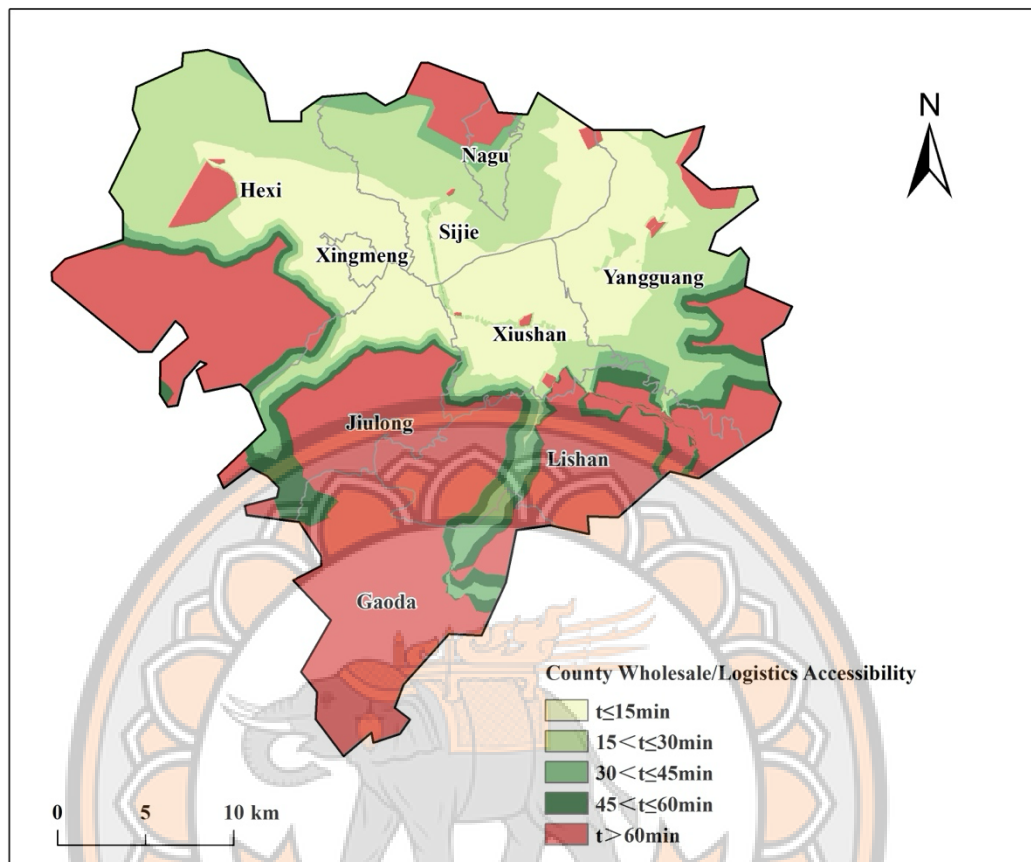


Figure 9 Standardized County-Level Wholesale and Logistics Accessibility Map

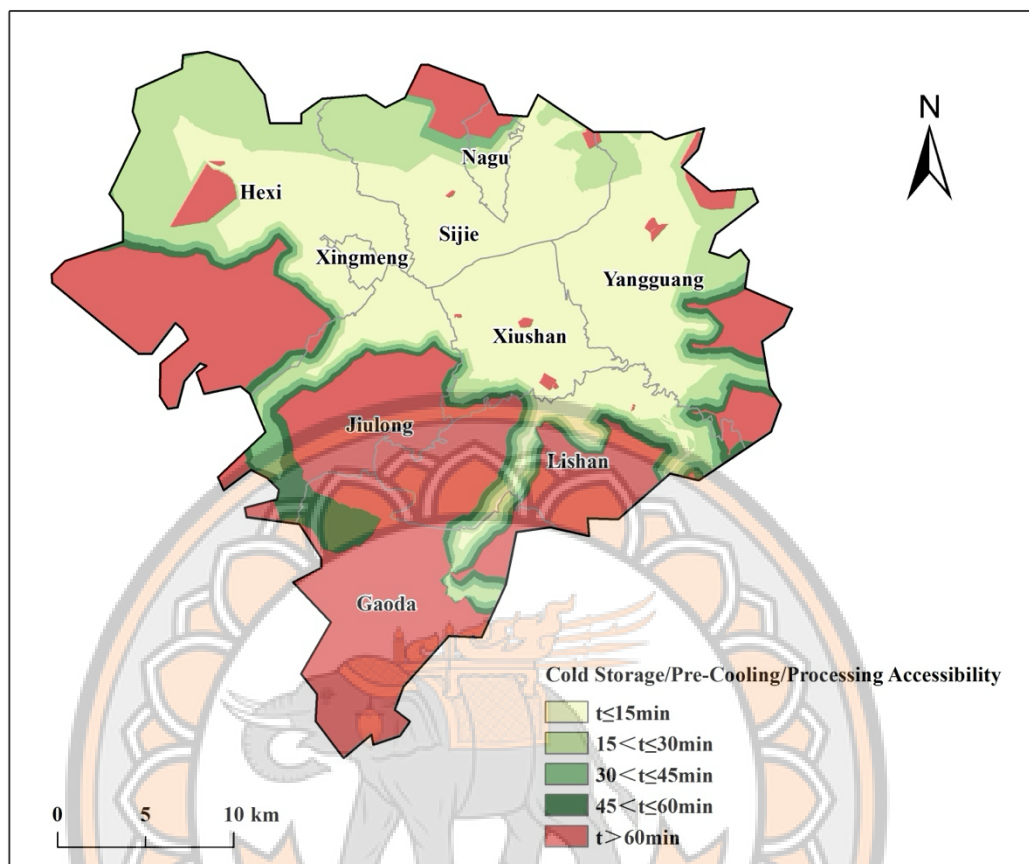


Figure 10 Standardized Cold Storage, Pre-Cooling and Processing Accessibility Map

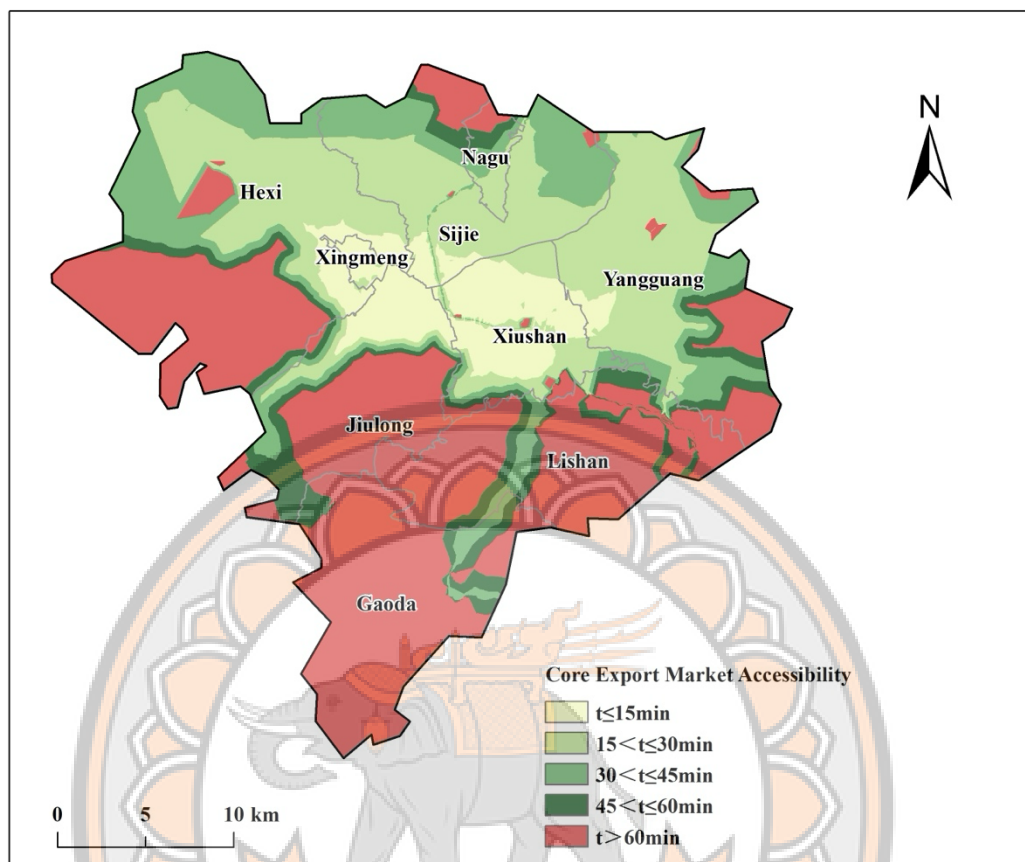


Figure 11 Standardized Core Export Market Accessibility Map

High main-road accessibility is concentrated in Sijie, Xingmeng, Xiushan, Yangguang, and central Hexi, particularly along major road corridors. High accessibility to county-level wholesale and logistics hubs is concentrated in Sijie, Xingmeng, Xiushan, Yangguang, and east-central Hexi, extending toward southern Nagu. High accessibility to cold-storage, pre-cooling, and processing points is mainly distributed in Sijie, Xingmeng, Xiushan, and western Yangguang, forming relatively continuous zones along major roads. High accessibility to core export markets is concentrated in Xingmeng, Sijie, Xiushan, and surrounding areas, with parts of Yangguang, Hexi, and Nagu also showing favorable access. These patterns demonstrate that supply-chain accessibility declines toward the mountainous periphery, especially in Jiulong, Lishan, and Gaoda.

3) Standardization Results for Social Factors

The standardized suitability results for agricultural labor density and rural public-service accessibility are shown in Figures 12 and 13.

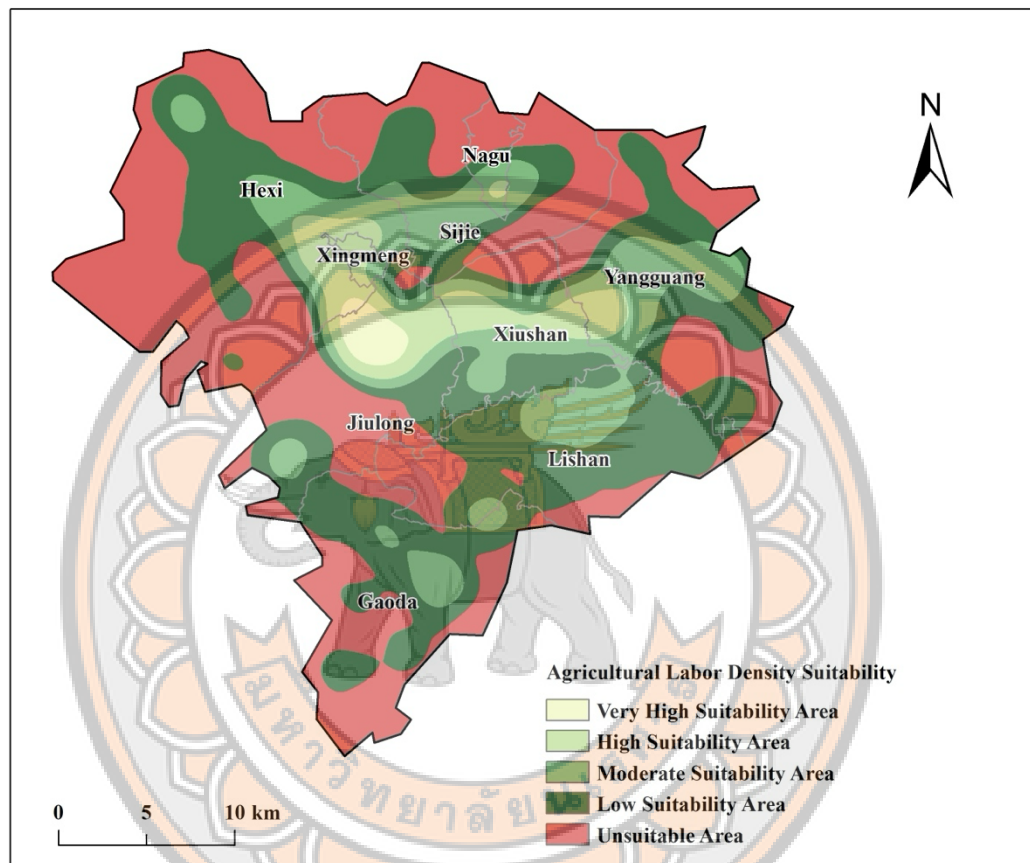


Figure 12 Standardized Agricultural Labor Density Suitability Map

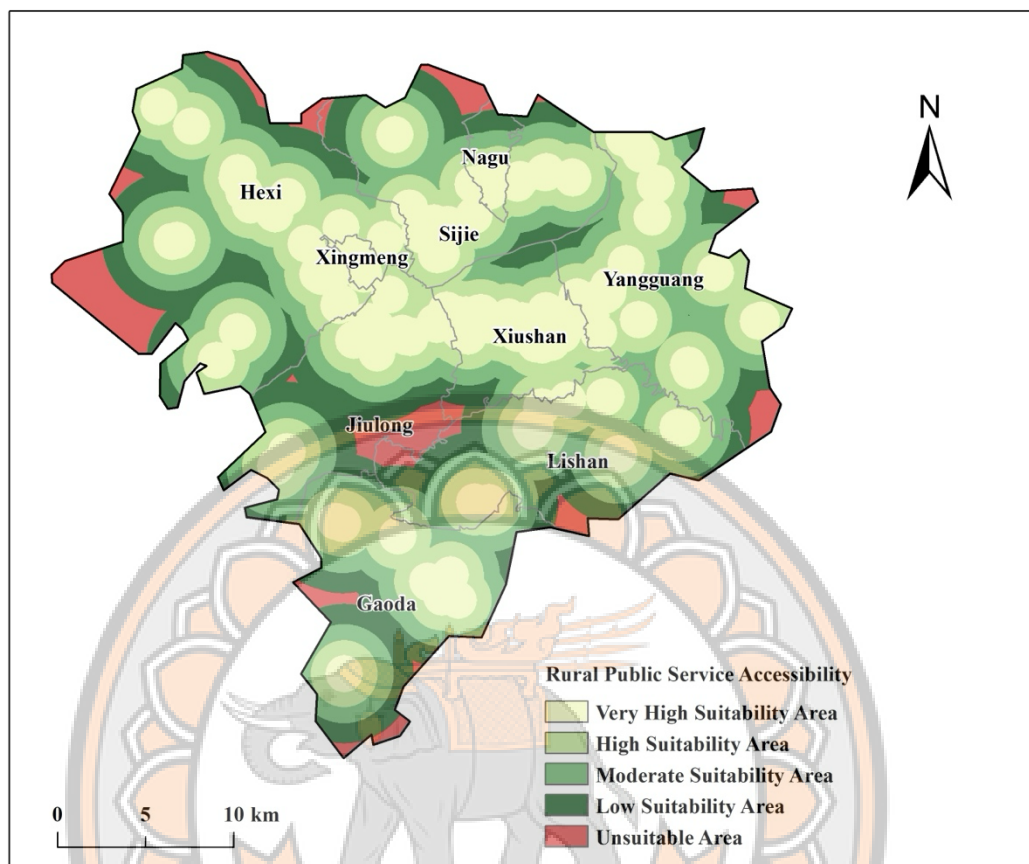


Figure 13 Standardized Rural Public Service Accessibility Map

High agricultural labor-density scores are concentrated in Xingmeng, western and central Xiushan, and surrounding areas, with additional higher-score zones in Sijie, eastern Hexi, and western Yangguang. These areas have relatively concentrated settlements and agricultural activity, which can support vegetable growing, field management, and harvesting. Low-scoring areas are more common in western Hexi, northern Nagu, Jiulong, Gaoda, and parts of the county periphery.

High rural public-service accessibility is concentrated in Sijie, Xingmeng, Xiushan, Yangguang, and Hexi, with multiple circular or clustered high-value areas around service facilities. Scores decline as travel time increases, and accessibility is generally lower in Jiulong, Gaoda, and peripheral areas. Although social factors have lower overall weights than natural and economic factors, they provide

supporting conditions through labor availability and access to production-related services.

4.3.3 Spatial Processing of Constraint Conditions

At the indicator-system development stage, ecological conservation red lines and protected areas, drinking-water source protection zones and buffer areas, and permanent basic farmland were identified as three potential categories of spatial constraints. Their purpose was to ensure that vegetable growing-area selection considered ecological security, water-environment protection, and farmland-use controls.

For ecological conservation red lines and protected areas, complete and precise vector boundaries for Tonghai County were not available under the data-access conditions of this study. Existing public information and spatial data did not identify a protected area that could be directly incorporated into the analysis. Consequently, this category was documented but not included in the operational GIS mask.

For drinking-water source protection zones and buffer areas, official complete vector boundaries were not available. An operational proxy was therefore constructed using OpenStreetMap water-body data. Qilu Lake and other water bodies were extracted, and a 200 m buffer was created outward from the shoreline. The water bodies and their buffer zones were treated as water-environment protection constraints to avoid prioritizing large-scale vegetable production close to major water bodies.

Permanent basic farmland was not treated as an exclusion mask because vegetable growing is an agricultural land use and does not inherently conflict with farmland protection. However, the subsequent recommendations emphasize maintaining agricultural use and ensuring that cold-storage, processing, or logistics facilities comply with land-use controls. The data sources and spatial-processing methods for the constraint factors are summarized in Table 25.

Table 25 Data Sources and Spatial Processing Methods of Constraint Factors

Constraint Factor	Data Source	Verification and Processing Result	Included in Mask	Spatial Processing Method
Ecological conservation red lines and protected areas	Public planning materials and spatial-data verification	Precise boundary unavailable; no protected area identified for inclusion	No	Documented in text; not spatially excluded
Drinking-water source protection areas and buffer zones	OSM water-body data	Qilu Lake and other water bodies extracted; 200 m buffer constructed as proxy	Yes	Water bodies and buffer = 0; other areas = 1
Permanent basic farmland	Planning and farmland-protection documents	No automatic prohibition on normal vegetable growing was identified	No	Not included in the main constraint mask; addressed in the policy recommendations

After verification, only water bodies and the 200 m buffer were included in the operational GIS constraint mask. The mask was converted to the same coordinate system, 30 m cell size, analysis extent, and grid alignment as the C1-C9 rasters. Water bodies and their buffer zones were assigned a value of 0, while other areas were assigned a value of 1. The Boolean mask was applied after comprehensive suitability calculation. The resulting constraint mask is shown in Figure 14.

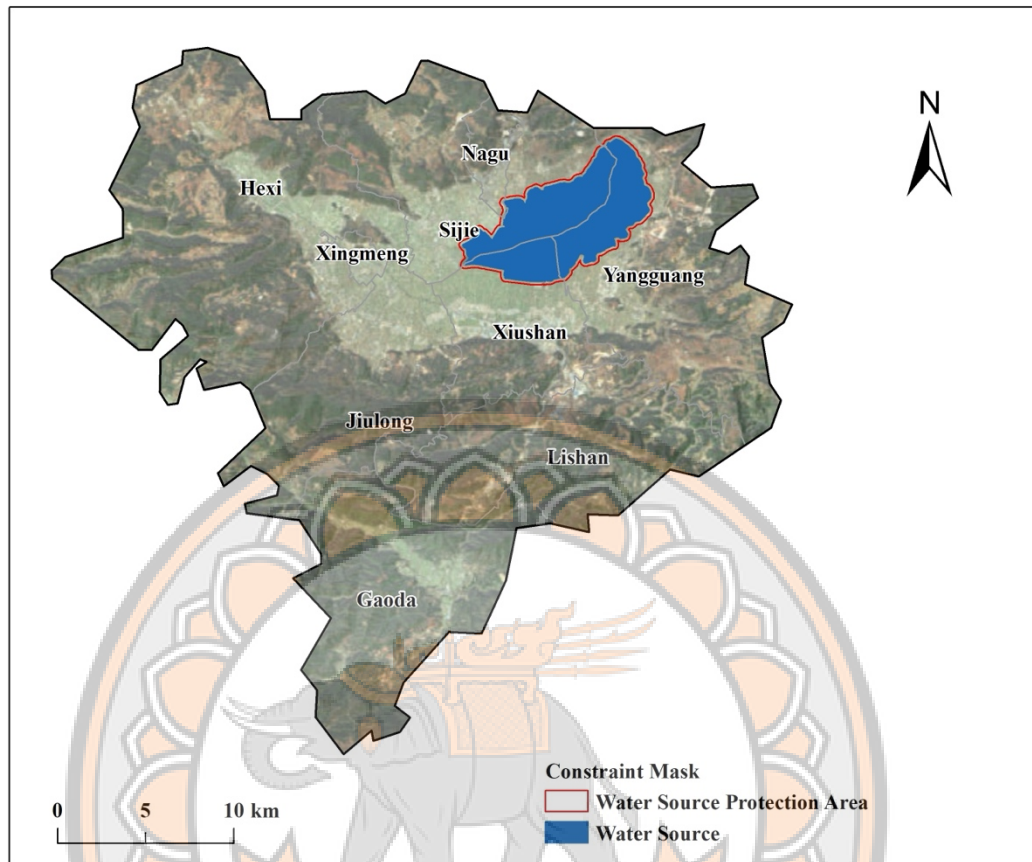


Figure 14 Constraint Mask for Vegetable Growing Area Selection in Tonghai County

4.4 Comprehensive Suitability Evaluation Results

4.4.1 Construction of the Comprehensive Suitability Evaluation Model

After standardization and weight calculation, the nine evaluation factors were integrated using the Weighted Linear Combination (WLC) method. The model is expressed as follows:

$$S = \sum_{i=1}^9 w_i C_i \quad (4-1)$$

Where:

S is the comprehensive suitability index.

w_i is the overall weight of evaluation factor i .

C_i is the standardized suitability score of evaluation factor i , $i = 1, 2, \dots, 9$.

Based on the calculated weights, the operational model was:

$$S = 0.1027 C_1 + 0.1089 C_2 + 0.2292 C_3 + 0.0488 C_4 + 0.0750 C_5 + 0.0826 C_6 + 0.1882 C_7 + 0.1032 C_8 + 0.0613 C_9$$

Because the displayed weights were rounded to four decimal places and sum to 0.9999, the GIS calculation used the unrounded weights or normalized the rounded weights to sum to 1. The standardized raster of each factor was multiplied by its corresponding weight and summed in the raster calculator to generate the pre-constraint comprehensive suitability raster. Integrating AHP with GIS-based weighted overlay enables expert judgments, natural conditions, and socioeconomic factors to be converted into a spatially continuous suitability surface, a procedure widely applied in agricultural land and crop-suitability assessment (Han et al., 2021a; Kihoro et al., 2013).

4.4.2 Classification Criteria for Suitability Levels

To facilitate interpretation, the pre-constraint comprehensive suitability index was classified into five levels using the Jenks natural breaks method: Unsuitable, Low Suitability, Moderate Suitability, High Suitability, and Very High Suitability. Higher values indicate stronger combined advantages in natural production conditions, supply-chain location, and social support. The four internal breakpoints were 2.141232, 2.684102, 3.308403, and 3.919133. The classification criteria and corresponding suitability levels are summarized in Table 26.

Table 26 Classification Criteria for Comprehensive Suitability Levels

Parameter	Threshold	Suitability Level	Comprehensive Suitability Index Range
a	2.141232	Unsuitable	$S < 2.141232$
b	2.684102	Low Suitability	$2.141232 \leq S < 2.684102$
c	3.308403	Moderate Suitability	$2.684102 \leq S < 3.308403$
d	3.919133	High Suitability	$3.308403 \leq S < 3.919133$
-	-	Very High Suitability	$S \geq 3.919133$

The same thresholds were used for the pre-constraint suitability map, the final post-constraint suitability map, and all sensitivity-analysis scenarios. This fixed-threshold approach ensures comparability among scenarios. High and Very High Suitability areas are collectively referred to as high-quality suitable areas.

4.4.3 Spatial Distribution of Vegetable-Growing Suitability

The comprehensive suitability index was classified into five levels using the Jenks natural breaks method.

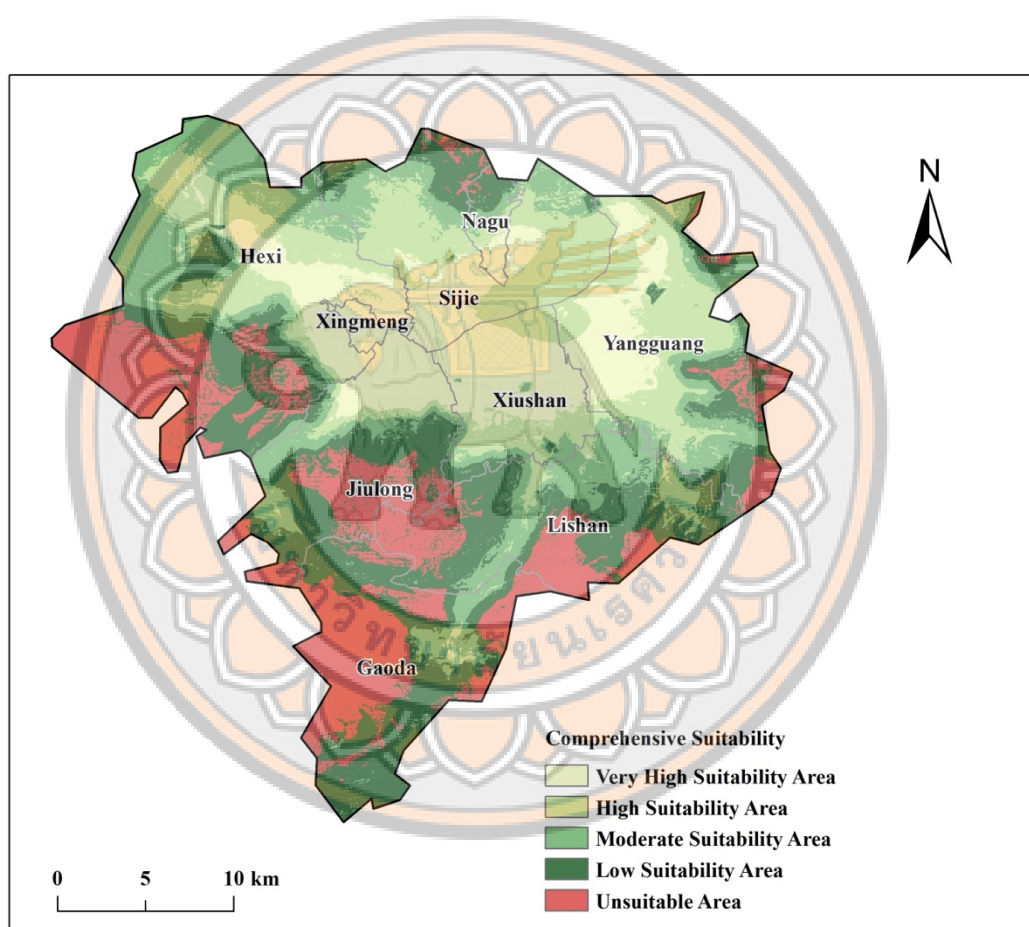


Figure 15 Comprehensive Suitability Map of Vegetable Growing Areas in Tonghai County

Figure 15 shows a clear spatial differentiation of comprehensive suitability in Tonghai County. Very High Suitability areas are concentrated mainly in the central lake-basin and flatland areas, particularly in Xingmeng, Sijie, Xiushan, and Yangguang, where they form relatively continuous patches and belts. High Suitability areas are distributed mainly around the Very High Suitability zones and extend toward Hexi, Yangguang, and the north-central part of the county.

Moderate Suitability areas are located primarily in the transition zone between the central favorable area and the peripheral mountains. Low Suitability and Unsuitable areas are concentrated in the western, southern, and southeastern mountainous margins, especially in Jiulong, Lishan, and Gaoda. These areas are generally constrained by steeper slopes, weaker soil conditions, or longer travel times to supply-chain facilities.

Overall, higher-suitability areas are concentrated in the central basin where terrain is relatively gentle, temperature and soil conditions are favorable, and access to roads, markets, and cold-chain facilities is stronger. Lower-suitability areas are more common in peripheral mountainous zones, reflecting the combined effects of natural conditions, supply-chain location, and social support.

To further compare the area of different suitability levels, the area of each level was calculated from the vectorized boundaries of the classification result.

Table 27 Area Statistics of Comprehensive Suitability Levels

Suitability Level	Area (ha)	Area Proportion (%)
Very High Suitability	12584.70	17.15
High Suitability	14582.07	19.87
Moderate Suitability	13828.23	18.84
Low Suitability	18072.63	24.63
Unsuitable	14317.29	19.51
Total	73384.92	100.00

As shown in Table 27, before constraint exclusion, the Very High Suitability area covered 12,584.70 ha, accounting for 17.15% of the effective

comprehensive evaluation area. The High Suitability area covered 14,582.07 ha, accounting for 19.87%, while the Moderate Suitability area covered 13,828.23 ha, accounting for 18.84%. The Low Suitability and Unsuitable areas covered 18,072.63 ha and 14,317.29 ha, representing 24.63% and 19.51%, respectively.

The combined High and Very High Suitability area was 27,166.77 ha, accounting for 37.02% of the effective comprehensive evaluation area. This indicates that Tonghai County contains a considerable area with favorable conditions for vegetable growing before water-environment constraints are considered. However, this result mainly represents theoretical suitability based on the combined effects of the evaluation factors and therefore requires further adjustment using the water bodies and their 200 m buffer zones.

4.4.4 Area Statistics after Constraint Exclusion

The water bodies and their 200 m buffer zones were overlaid on the comprehensive suitability map to obtain the final suitability map shown in Figure 16.

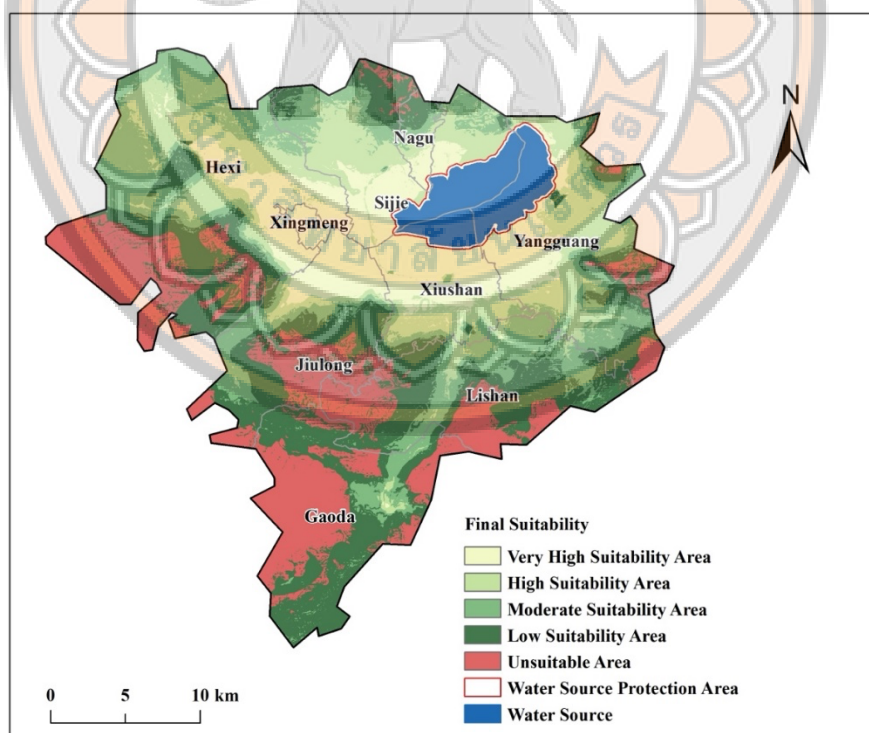


Figure 16 Final Suitability Map of Vegetable Growing Areas in Tonghai County after Constraint Exclusion

After constraint exclusion, Qilu Lake and surrounding buffer areas are classified as Restricted Area. Very High Suitability areas remain concentrated mainly in Xingmeng, Sijie, Xiushan, and Yangguang, while High Suitability areas occur around these cores and extend toward Hexi and the north-central part of the county. Moderate, Low, and Unsuitable areas maintain their general transition toward the mountainous periphery.

Some locations that scored as High or Very High Suitability in the unconstrained evaluation were reclassified as Restricted Area because they overlap Qilu Lake or the 200 m buffer. This demonstrates that areas with favorable production and supply-chain conditions may still be inappropriate for new large-scale vegetable development when water-environment protection is considered.

Table 28 Area Statistics of Final Suitability Levels after Constraint Exclusion

Final Suitability Level	Area (ha)	Proportion of Evaluation Area (%)	Proportion of Non-Restricted Area (%)
Very High Suitability	11220.48	15.29	16.22
High Suitability	11740.32	16.00	16.97
Moderate Suitability	13828.23	18.84	19.99
Low Suitability	18072.63	24.63	26.12
Unsuitable	14317.29	19.51	20.70
Restricted Area	4205.97	5.73	—
Total	73384.92	100.00	100.00

Note: Proportions of the total evaluation area were calculated using 73,384.92 ha as the denominator, while proportions of the non-restricted evaluation area were calculated using 69,178.95 ha as the denominator. The Restricted Area was calculated as the difference between the evaluation areas before and after constraint exclusion.

As shown in Table 28, after constraint exclusion, the Very High Suitability area covered 11,220.48 ha, accounting for 16.22% of the non-restricted evaluation area. The High Suitability area covered 11,740.32 ha, accounting for 16.97%, while the Moderate Suitability area covered 13,828.23 ha, accounting for 19.99%. The Low Suitability and Unsuitable areas covered 18,072.63 ha and 14,317.29 ha, representing 26.12% and 20.70%, respectively.

The combined High and Very High Suitability area was 22,960.80 ha, accounting for 33.19% of the non-restricted evaluation area. These areas constitute the principal priority areas for vegetable growing-area selection in Tonghai County. The Restricted Area covered 4,205.97 ha, accounting for 5.73% of the effective evaluation area.

Compared with the results before constraint exclusion, the Very High Suitability area decreased by 1,364.22 ha, while the High Suitability area decreased by 2,841.75 ha. Together, these two classes decreased by 4,205.97 ha. The areas of the Moderate, Low, and Unsuitable classes remained unchanged, indicating that the water bodies and their 200 m buffer zones mainly overlapped with areas originally classified as High or Very High Suitability.

4.5 Site-Selection Results and Discussion

4.5.1 Identification of Priority Growing Areas

Based on the final suitability classification after constraint exclusion, the High and Very High Suitability areas were identified as priority areas for vegetable growing in Tonghai County. These areas have relatively favorable natural production conditions, supply-chain accessibility, and social-support conditions, while remaining outside the water bodies and their 200 m buffer zones.

As shown in Figure 16 and Table 28, the priority areas covered a total of 22,960.80 ha, accounting for 33.19% of the non-restricted evaluation area. Of this total, the Very High Suitability area covered 11,220.48 ha and the High Suitability area covered 11,740.32 ha.

Spatially, the priority zones are concentrated in the central lake-basin area, with Xingmeng, Sijie, Xiushan, and Yangguang forming the principal core and Hexi and surrounding flat areas forming extensions. Very High Suitability areas are

appropriate for stabilizing and upgrading existing production, while High Suitability areas represent potential optimization zones where road connections, cold-chain services, or production organization can be improved.

Identification as a priority area does not imply unrestricted development. Any proposed project must still comply with statutory land-use controls, environmental-protection requirements, and project-level approval procedures. Cold storage, logistics parks, processing facilities, and other non-agricultural construction require separate compliance review under territorial spatial planning and land-use regulations.

4.5.2 Causes of High- and Low-Suitability Areas

The formation of Very High Suitability areas results from the combined effects of natural, economic, and social conditions. The central basin has relatively gentle slopes, suitable temperatures, and generally favorable soil conditions. At the same time, travel times to trunk roads, wholesale and logistics hubs, cold-chain facilities, and core export markets are comparatively short. Settlement concentration and agricultural activity also provide labor and service support.

High Suitability areas have conditions similar to those of the Very High Suitability class but typically contain one or more relative weaknesses. Some have strong natural conditions but longer travel times to cold-chain facilities or export-market nodes, while others have good supply-chain accessibility but slightly weaker slope or soil conditions. These areas retain strong production potential but require targeted improvements.

Low Suitability and Unsuitable areas are concentrated in the mountainous periphery, where steep terrain, difficult mechanization, higher road-development costs, and weak accessibility to logistics, cold-chain, and market facilities may occur simultaneously. Low settlement density and weaker rural-service accessibility further reduce their suitability for large-scale, export-oriented vegetable growing.

4.5.3 Effects of Key Factors

The AHP results identify soil organic matter, travel time to core export markets, and annual average temperature as the three indicators with the highest overall weights. Soil organic matter received the largest weight (0.2292), reflecting the

importance of fertility, soil structure, and water- and nutrient-retention capacity for intensive vegetable production.

Travel time to core export markets ranked second (0.1882). Tonghai's vegetable industry is highly commercialized and export-oriented, and vegetable products are perishable and sensitive to logistics timeliness. Shorter market travel times can reduce transport losses and improve market responsiveness, making this indicator a major determinant of high-suitability areas.

Annual average temperature, agricultural labor density, and slope received weights of 0.1089, 0.1032, and 0.1027, respectively. Temperature provides a basic production condition, settlement density represents potential labor and agricultural activity concentration, and gentle slopes support mechanization, irrigation, and scale operation. The remaining road, wholesale/logistics, cold-chain, and public-service indicators have lower individual weights but jointly determine the efficiency of the production-to-market connection.

4.5.4 Reasonableness of Results and Matching with Existing Layout

Because official parcel-level data on existing vegetable growing areas were not publicly available under the data-access conditions of this study, an existing vegetable growing-area proxy dataset was constructed from CLCD cropland data, the locations of villages with concentrated vegetable production, and contiguous cropland polygons of at least 1 ha.

To examine the relationship between the model results and the existing vegetable-production pattern, an existing vegetable growing-area proxy dataset was constructed from CLCD cropland data, the locations of villages with concentrated vegetable production, and contiguous cropland polygons of at least 1 ha. The spatial distribution of the resulting existing vegetable growing-area proxy is shown in Figure 17.

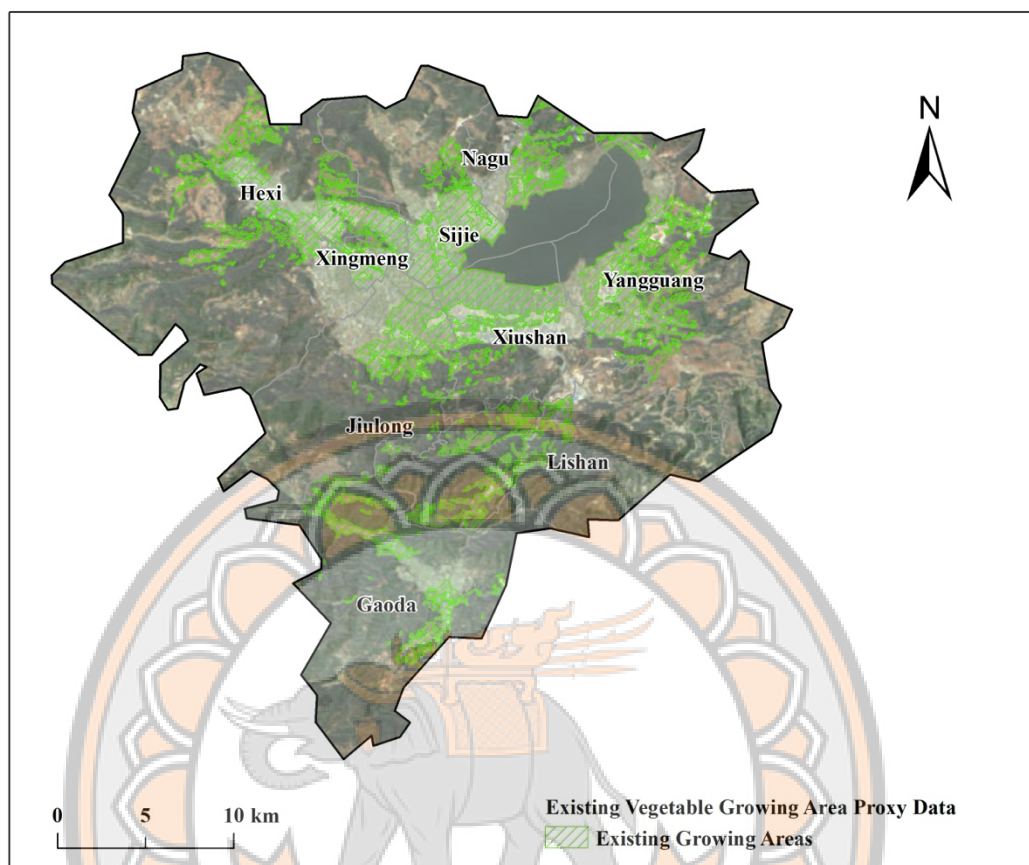


Figure 17 Distribution of Existing Vegetable Growing Area Proxy Data in Tonghai County

The proxy areas are concentrated mainly in the central basin and flat cultivated areas, particularly in Xingmeng, Sijie, Xiushan, Yangguang, and Hexi, while extending in linear and patchy forms along valleys and relatively flat farmland in Jiulong, Lishan, and Gaoda. Because the proxy was derived from public land-cover data and production-village information rather than parcel-level field surveys, it represents an approximate spatial pattern rather than an exact map of vegetable cultivation.

Overlaying the proxy with the final suitability map provides a practical check of the model's spatial explanatory capacity. Comparing current land use or observed crop distribution with model-derived suitability is a commonly used validation approach, although it does not replace independent field verification (Kihoro et al., 2013; Radočaj et al., 2020) .

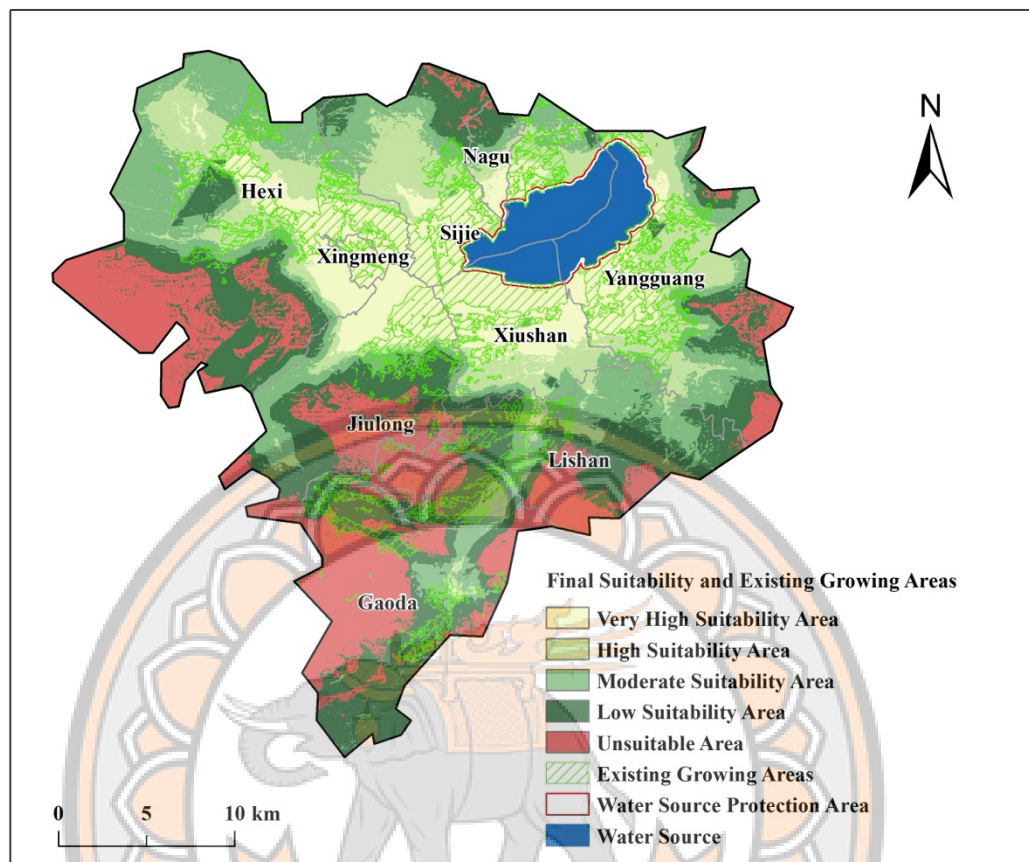


Figure 18 Overlay of Final Suitability Levels and Existing Vegetable Growing Areas in Tonghai County

As shown in Figure 18 the existing vegetable growing-area proxy exhibits a clear spatial overlap with the Very High and High Suitability areas. This overlap is particularly evident in the central parts of the county, including Xingmeng, Sijie, Xiushan, and Yangguang. The result indicates a reasonable level of spatial consistency between the advantageous areas identified by the model and the existing concentration of vegetable production.

At the same time, some polygons in the existing growing-area proxy are located within the Moderate, Low, and Unsuitable areas, mainly in the southern and peripheral parts of the county. This pattern may be associated with the historical development of the existing growing layout, land availability, local infrastructure conditions, and the operational decisions of agricultural producers. It may also be

influenced by the accuracy limitations of the proxy dataset. Overall, the overlay results provide spatial evidence supporting the basic reasonableness of the evaluation results, while also indicating that some areas represented by the proxy may still have room for further optimization and improvement.

Table 29 Distribution of the Existing Vegetable Growing-Area Proxy across Comprehensive Suitability Levels

Comprehensive Suitability Level	Proxy Area (ha)	Proportion of Total Proxy Area (%)
Very High Suitability	6247.41	51.06
High Suitability	2573.26	21.03
Moderate Suitability	1473.57	12.04
Low Suitability	1686.49	13.78
Unsuitable	254.74	2.08
Total	12235.47	100.00

Note: The table reports the distribution of the existing vegetable growing-area proxy across the pre-constraint comprehensive suitability levels. Of the total proxy area, 376.65 ha overlaps the water bodies and their 200 m buffer zones, accounting for 3.08%. This overlap is already included in the suitability-level areas shown above and is therefore reported separately rather than added as an additional category.

As shown in Table 29, 72.09% of the existing growing-area proxy was distributed within the pre-constraint High and Very High Suitability classes, while 27.91% was located within the Moderate, Low, and Unsuitable classes. Of the total proxy area, 376.65 ha, or 3.08%, overlapped the water bodies and their 200 m buffer zones. After accounting for this restricted-area overlap, approximately 69.01% of the total proxy area remained within the non-restricted High and Very High Suitability areas. These results indicate a generally clear spatial correspondence between the existing growing-area proxy and the model-identified favorable zones, although some proxy areas are located in less suitable or environmentally restricted locations.

4.5.5 Sensitivity Analysis

To examine the sensitivity of the AHP-GIS comprehensive evaluation model to changes in the criteria-layer weights, this study applied a one-at-a-time (OAT) criteria-layer weight perturbation of $\pm 10\%$. The total weights of the natural, economic, and social criteria layers were increased and decreased by 10%, respectively, while the relative weights of the evaluation indicators within each criteria layer were held constant. After one criteria-layer weight was adjusted, the weights of the other two criteria layers were proportionally rescaled according to their original weight ratio to ensure that the sum of all evaluation indicator weights remained equal to 1.

Because WLC results may be affected by indicator standardization, weight settings, and classification methods, sensitivity testing helps determine whether the evaluation results are overly dependent on a particular set of initial parameters (Yin et al., 2020).

Based on the adjusted criteria-layer weights, the overall weights of the nine evaluation indicators, C1-C9, were recalculated for six perturbation scenarios by multiplying the adjusted criteria-layer weights by the corresponding local indicator weights. The comprehensive suitability result for each scenario was then recalculated using the weighted overlay tool in ArcGIS. To ensure comparability across scenarios, all perturbation scenarios used the suitability classification thresholds established under the baseline scenario.

Because the Very High Suitability area was relatively limited, analyzing it separately could make the result sensitive to cell changes near the classification thresholds. Therefore, the High and Very High Suitability areas were combined and are

hereafter referred to as the high-quality suitable area. Their combined area was used as the principal measure in the sensitivity analysis. The area of the high-quality suitable zone under each perturbation scenario was calculated, and its rate of change relative to the baseline scenario was used to evaluate the response of the model to changes in criteria-layer weights. The relative change rate was calculated as follows:

$$R_j = \frac{A_j - A_0}{A_0} \times 100\% \quad (4-2)$$

where R_j represents the relative change rate in the high-quality suitable area under perturbation scenario j , A_j represents the high-quality suitable area under scenario j , and A_0 represents the high-quality suitable area under the baseline scenario.

Because the water bodies and their 200 m buffer zones constitute a fixed constraint layer and do not change with the evaluation weights, the sensitivity analysis was conducted using the comprehensive suitability result before constraint exclusion. Therefore, the high-quality suitable area under the baseline scenario was the combined High and Very High Suitability area reported in Table 30, totaling 27,166.77 ha.

Table 30 Sensitivity Analysis Results under Criteria-Layer Weight Perturbations

Perturbation Scenario	High-Quality Suitable Area (ha)	Area Change from Baseline (ha)	Relative Change Rate (%)
Baseline Scenario	27166.77	0	0
Natural-Factor Weight +10%	27212.04	45.27	0.17
Natural-Factor Weight -10%	27262.53	95.76	0.35
Economic-Factor Weight +10%	27845.19	678.42	2.50
Economic-Factor Weight -10%	26556.66	-610.11	-2.25
Social-Factor Weight +10%	26905.86	-260.91	-0.96
Social-Factor Weight -10%	27618.75	451.98	1.66

Note: The high-quality suitable area refers to the combined area of the High and Very High Suitability levels.

As shown in Table 30, the total high-quality suitable area under the baseline scenario was 27,166.77 ha. When the natural-factor weight was increased and decreased by 10%, the high-quality suitable areas were 27,212.04 ha and 27,262.53 ha, respectively, corresponding to relative change rates of 0.17% and 0.35%. These results indicate that small changes in the natural-factor weight had only a limited effect on the total high-quality suitable area.

When the economic-factor weight was increased and decreased by 10%, the high-quality suitable areas were 27,845.19 ha and 26,556.66 ha, respectively, with relative change rates of 2.50% and -2.25%. Increasing the economic-factor weight expanded the high-quality suitable area, whereas decreasing it reduced the area. The economic-factor perturbations produced the largest changes among the three criteria layers, indicating that market location, transportation accessibility, logistics services, and cold-chain and pre-cooling facilities exert a relatively strong influence on the size of the high-quality suitable area.

When the social-factor weight was increased and decreased by 10%, the high-quality suitable areas were 26,905.86 ha and 27,618.75 ha, respectively, corresponding to relative change rates of -0.96% and 1.66%. Increasing the social-factor weight resulted in a slight reduction in the high-quality suitable area, whereas decreasing it led to a modest expansion. The overall magnitude of change remained lower than that observed under the economic-factor perturbations.

Overall, across the six criteria-layer perturbation scenarios, the absolute relative change rates in the high-quality suitable area ranged from 0.17% to 2.50%, all below the 5% threshold adopted in this study. Therefore, within the $\pm 10\%$ criteria-layer weight perturbation range, modest changes in the weights did not cause substantial changes in the total size of the high-quality suitable area. This indicates that the model demonstrates relatively good robustness in terms of area statistics. It should be noted that the sensitivity analysis mainly reflects changes in the total area of high-quality suitable zones and does not demonstrate that the spatial locations of all suitable patches remained unchanged.

4.6 Chapter Summary

This chapter applied the evaluation indicator system and AHP-GIS model to Tonghai County. Nine valid expert questionnaires were aggregated to construct group judgment matrices, and all matrices passed the consistency test. The final weights show that soil organic matter and accessibility to core export markets are the most influential indicators, confirming the combined importance of production conditions and supply-chain efficiency.

The nine evaluation factors were spatialized and standardized to a common 1–5 scale. The Weighted Linear Combination (WLC) method was then used to generate the comprehensive suitability surface, and a Boolean mask representing water bodies and their 200 m buffer zones was applied to obtain the final suitability result. Before constraint exclusion, the combined High and Very High Suitability area was 27,166.77 ha, accounting for 37.02% of the effective comprehensive evaluation area. After constraint exclusion, the combined area decreased to 22,960.80 ha, accounting for 33.19% of the non-restricted evaluation area. The most favorable areas were concentrated in the central lake-basin and flatland zones, especially around Xingmeng, Sijie, Xiushan, and Yangguang, whereas lower-suitability areas were concentrated in the mountainous peripheral areas.

The existing vegetable growing-area proxy showed a clear spatial correspondence with the model-identified High and Very High Suitability areas, providing spatial support for the general reasonableness of the evaluation results. The sensitivity analysis showed that, under $\pm 10\%$ criteria-layer weight perturbations, the absolute relative change in the high-quality suitable area ranged from 0.17% to 2.50%, with economic-factor perturbations producing the largest changes. Overall, the model demonstrated relatively good robustness in terms of the total high-quality suitable area. These findings provide the empirical basis for the conclusions and supply-chain-oriented recommendations presented in Chapter 5.

CHAPTER V

CONCLUSION

Using Tonghai County, Yunnan Province, as a case study, this research examined the spatial selection of export-oriented vegetable growing areas by integrating natural production conditions with logistics and supply-chain efficiency within a unified evaluation framework. Based on research on agricultural land suitability, agricultural supply chains, logistics accessibility, and AHP-GIS methods, the study developed an evaluation system consisting of natural, economic, and social factors. AHP was used to determine the relative weights of the indicators, while GIS was used to process multi-source spatial data, standardize the evaluation factors, perform weighted overlay, apply spatial constraints, and compare the modeled results with an existing vegetable growing-area proxy.

Unlike conventional land-suitability studies that focus primarily on whether an area can support crop production, this study also assessed whether vegetable-production areas can connect efficiently with trunk transportation routes, wholesale and logistics hubs, cold-chain facilities, and export markets. The findings therefore provide references for optimizing vegetable-production space, logistics-node layout, cold-chain infrastructure, and export-oriented supply-chain coordination in Tonghai County.

5.1 Research Conclusions

5.1.1 Indicator System and Model

This study constructed a hierarchical evaluation system for vegetable growing-area selection based on the production and distribution characteristics of Tonghai County's export-oriented vegetable industry. The evaluation system comprises three criteria layers and nine scoring indicators. Natural factors include slope, annual average temperature, and soil organic matter. Economic factors include travel time to main roads, county-level wholesale and logistics hubs, cold-storage/pre-cooling/processing points, and core export markets. Social factors include agricultural labor density and travel time to rural public services.

The indicator system reflects an integrated “production conditions-logistics connectivity-market accessibility” site-selection logic. Natural factors determine whether an area has a stable production foundation, while roads, logistics hubs, cold-chain facilities, and market accessibility determine whether harvested vegetables can enter the supply chain in a timely manner. For perishable and export-oriented products, production suitability and supply-chain efficiency must be considered together (Han et al., 2021a; Yin et al., 2020).

The expert questionnaire and AHP results show that soil organic matter has the highest overall weight (0.2292), followed by travel time to core export markets (0.1882). Annual average temperature, agricultural labor density, and slope also receive relatively high weights. This structure indicates that soil and other natural production conditions remain fundamental, but market access and logistics timeliness are also central to the spatial layout of Tonghai County’s vegetable industry.

The GIS implementation standardized all indicators to a common 1-5 scale and integrated them through weighted linear combination. Potential spatial constraints were verified separately, and water bodies with a 200 m buffer were included as the operational constraint layer. The combined structure of suitability scoring and constraint masking distinguishes relative suitability from basic environmental compliance and makes the results more relevant to practical planning.

Overall, the AHP-GIS framework integrates expert knowledge, natural production conditions, and supply-chain location into a single spatial model. It extends conventional land-suitability assessment by evaluating both production conditions and the accessibility of subsequent logistics and market links.

5.1.2 Suitability Evaluation Results

The comprehensive evaluation reveals clear spatial differentiation in Tonghai County. Higher-suitability areas are concentrated mainly in the central lake basin and flatland areas, particularly in Xingmeng, Sijie, Xiushan, and Yangguang, with extensions toward Hexi and nearby areas.

These areas combine relatively gentle slopes, suitable thermal conditions, and favorable agricultural foundations with shorter travel times to major roads, wholesale and logistics hubs, cold-chain nodes, and market destinations. The pattern demonstrates that high suitability is not determined by natural conditions alone but

results from the combined effects of production conditions and supply-chain accessibility.

Moderate Suitability areas are distributed mainly around the higher-suitability core and generally possess only part of the required advantages. Their main weaknesses may include soil fertility, road accessibility, cold-chain service coverage, or market travel time. Some of these areas could be upgraded through targeted infrastructure or service improvements.

Low Suitability and Unsuitable areas are concentrated in Jiulong, Lishan, Gaoda, and the mountainous western, southern, and southeastern peripheries. Steep terrain, weaker mechanization conditions, longer travel times, and limited cold-chain and logistics services reduce their attractiveness for new large-scale export-oriented vegetable production.

Applying the water-body and 200 m buffer mask excludes environmentally sensitive areas around Qilu Lake and other water bodies. This result confirms that a high suitability score does not automatically mean that an area should be developed. Final site selection must also comply with water-environment protection, land-use regulation, and other territorial spatial-control requirements.

5.1.3 Site-Selection and Supply-Chain Implications

The final High and Very High Suitability classes were identified as priority areas for the future optimization of vegetable production in Tonghai County. They are concentrated mainly in the central part of the county and display a pattern of clustered patches connected along major transportation corridors.

This spatial pattern highlights the interdependence between production bases and supply-chain nodes. For Tonghai County's export-oriented vegetable industry, site selection should not pursue natural suitability alone. It should also consider whether harvested products can rapidly reach collection points, pre-cooling facilities, sorting and packaging operations, and trunk transportation networks. When two sites have similar natural conditions, the site with better access to logistics hubs, cold-chain facilities, and markets has greater comprehensive value.

The high weight of travel time to core export markets indicates that markets are not merely an external destination after production; they are a key factor shaping the location of production bases. Using network travel time rather than straight-

line distance provides a more realistic representation of road conditions, spatial barriers, and market connectivity (Weiss et al., 2018) .

County-level wholesale and logistics hubs, cold-storage/pre-cooling/processing points, and main-road accessibility form the intermediate links between fields and markets. The first-mile connection from production areas to pre-cooling and cold-storage facilities directly affects postharvest quality and loss; therefore, storage location, facility capacity, and transportation organization should be planned together with the spatial distribution of production (Zhu et al., 2023).

The spatial overlay showed that 72.09% of the existing growing-area proxy was initially distributed within the High and Very High Suitability classes. After accounting for the 3.08% overlap with the Restricted Area, approximately 69.01% of the total proxy area remained within the non-restricted High and Very High Suitability areas. A further 27.91% was located within the Moderate, Low, and Unsuitable classes. These results indicate a generally clear spatial correspondence between the proxy dataset and the model-identified favorable zones.

The sensitivity analysis showed that, under $\pm 10\%$ criteria-layer weight perturbations, the absolute relative change in the high-quality suitable area ranged from 0.17% to 2.50%, indicating relatively good robustness in terms of total area. Economic-factor perturbations produced the largest changes, reinforcing the importance of transportation, logistics, cold-chain services, and market accessibility in vegetable growing-area selection. The principal implication is that Tonghai County should shift from isolated production-base planning toward coordinated planning of production bases, logistics nodes, cold-chain facilities, and export corridors.

5.2 Recommendations

5.2.1 Optimization of Growing Space

Tonghai County should adopt differentiated management strategies according to suitability level rather than relying on a simple expansion of growing area. In the Very High Suitability zones, planning should focus on maintaining existing production advantages, improving yield and quality, and strengthening supply-chain coordination. Standardized production, quality control, organized harvesting, and order-

based production should be aligned with cold-chain capacity, vehicle scheduling, and market demand.

High Suitability zones can serve as potential areas for spatial optimization and moderate expansion, subject to compliance with water-environment and land-use controls. Before expansion, the principal limiting factors of each area should be identified. Areas with good natural conditions but weak logistics services require improved collection roads, pre-cooling access, and transportation organization; areas with favorable logistics locations but moderate soil conditions require production-side improvement.

Moderate Suitability zones should be treated as areas for targeted improvement rather than immediate large-scale development. Improvements may include better field roads, shared cold-chain services, or product-structure adjustments. Expansion should occur only when the expected benefits justify the required investment.

Low Suitability and Unsuitable zones should not be prioritized for new export-oriented vegetable bases. Where vegetable production already exists in these areas, crop choice and production scale may be adjusted according to product storability, local market demand, and actual logistics conditions. Water bodies and the 200 m buffer should remain restricted areas. Suitability for vegetable growing should also not be confused with suitability for cold-storage, processing, or logistics construction, which requires separate land-use approval.

5.2.2 Improvement of Logistics and Cold-Chain Systems

The results indicate that market accessibility, cold-chain accessibility, and logistics-hub accessibility are major determinants of comprehensive suitability. Tonghai County should therefore strengthen coordination between production bases and supply-chain infrastructure rather than focusing only on production inputs.

First, collection networks should be optimized. Village-level or subregional collection points can be located according to the spatial distribution of priority growing areas, reducing fragmented and repeated transportation. These points should be close to both major production clusters and road networks so that vegetables can be consolidated, graded, and transferred shortly after harvest.

Second, pre-cooling and short-term cold-storage services should be strengthened. Early temperature control is critical to maintaining vegetable quality. Shared pre-cooling facilities should be prioritized in concentrated production areas with inadequate existing service but favorable road access. Cooperative facilities, third-party services, or mobile pre-cooling equipment can improve utilization where investment by individual producers is not economically feasible.

Third, transport organization between production bases and county-level wholesale or logistics hubs should be improved. Spatial accessibility alone does not determine actual supply-chain efficiency; vehicle scheduling, loading rates, waiting time, and dispatch frequency are also important. Collection routes should be coordinated with harvest cycles to reduce empty running and unnecessary transshipment.

Cold-chain networks include pre-cooling, storage, processing, refrigerated transportation, and distribution. The continuity and coordination of these links jointly determine product quality and logistics efficiency (Shi et al., 2024; Zhu et al., 2023).

In the longer term, Tonghai County should develop a multi-level network linking growing bases, collection points, pre-cooling and processing nodes, county logistics hubs, and external markets. The service areas and functions of different node levels should be coordinated to avoid both duplicated investment and service gaps.

5.2.3 Planning and Decision-Making by Stakeholders

For local government, the suitability results can support agricultural planning, logistics-infrastructure investment, and project screening, but they cannot replace formal territorial spatial planning or statutory land-use controls. Priority growing zones should be planned together with roads, cold-chain facilities, wholesale markets, and logistics nodes.

Infrastructure allocation should not be based solely on equal distribution by administrative unit. Cold-chain and logistics facilities should be located according to production scale, crop type, road-network conditions, and required service time. Public investment should focus on mismatches between concentrated production and existing logistics services.

Agricultural departments maintain information on production patterns and agricultural operators; transportation departments manage road-network and traffic data; natural-resources departments manage land-use controls; and commerce or market-regulation departments maintain information on wholesale and distribution nodes. Integrating these data is necessary to produce an implementable supply-chain-oriented location strategy.

For agricultural enterprises, cooperatives, and large-scale operators, location decisions should consider not only land rent and parcel size but also travel time to collection points, cold-chain facilities, logistics hubs, and target markets. Additional transport, pre-cooling, and loss costs should be incorporated into investment evaluation when a naturally suitable site is logistically weak.

Different vegetable categories also require differentiated location strategies. Highly perishable leafy vegetables should be prioritized in areas with strong cold-chain and market accessibility, while relatively storable products may be located in naturally favorable areas with somewhat longer market travel times. Matching product characteristics with spatial conditions can improve overall supply-chain performance.

5.3 Research Limitations

5.3.1 Limitations of Weight Determination

AHP converts expert judgments into indicator weights and provides consistency testing, but the final weights remain influenced by expert background, professional experience, and subjective cognition. Specialists in agriculture and soil science may emphasize production conditions, whereas logistics and supply-chain experts may assign greater importance to cold-chain, transportation, and market timeliness. Geometric aggregation reduces the influence of extreme individual judgments but does not eliminate subjectivity.

The expert sample was also relatively limited and did not fully represent all logistics enterprises, agricultural operators, farmers, and government departments. Future studies should expand the expert panel and compare the weight structures of different stakeholder groups.

5.3.2 Data and Spatial-Analysis Limitations

The study integrates multiple datasets that differ in year, spatial accuracy, completeness, and update frequency. Although all data were projected, clipped, rasterized, and standardized, spatial errors may remain.

Complete official vector data for ecological conservation red lines, protected areas, legal drinking-water source protection zones, and permanent basic farmland were not available. Therefore, the operational constraint analysis relied mainly on water bodies and a 200 m buffer as a proxy. This cannot fully substitute for statutory planning data held by government agencies.

The existing vegetable growing-area layer is a proxy derived from land-cover data and production-village information. It cannot fully identify actual crop type, seasonal rotation, or small dispersed parcels. The overlay therefore measures spatial correspondence rather than strict classification accuracy.

Agricultural labor density was represented by settlement-point density and does not directly measure the actual agricultural labor force. Travel-time surfaces were calculated using assigned road speeds and do not incorporate real-time congestion, seasonal road conditions, vehicle type, loading and unloading time, or facility capacity.

In addition, administrative-boundary matching, rasterization, spatial resolution, and the conversion of classified raster to vector boundaries may introduce minor differences in area statistics. In this study, the suitability classification was conducted within a common 30 m raster framework, while the final area statistics were summarized from the vectorized classification boundaries. Future research should use official administrative boundaries, higher-resolution spatial data, and field or authoritative datasets to further verify the spatial and area results.

5.3.3 Indicator and Model Limitations

The model represents supply-chain conditions primarily through spatial accessibility. It does not directly include logistics cost, cold-storage capacity, fleet size, transport frequency, product loss rate, or market transaction volume. Consequently, the model identifies areas with favorable spatial supply-chain conditions rather than areas with the mathematically lowest total logistics cost or highest operating profit.

Weighted linear combination allows compensation among indicators. For example, moderate soil conditions may be partly offset by strong transportation and market accessibility. This is useful for comprehensive comparison but may be overly compensatory for factors with strict minimum requirements.

The sensitivity analysis focuses on changes in the total High and Very High Suitability area after criteria-layer weight perturbation. It does not fully compare spatial location, patch structure, or overlap among scenarios. Therefore, the robustness conclusion applies mainly to the overall scale of favorable areas and does not demonstrate complete stability of the spatial pattern.

Finally, the study is a county-scale strategic assessment. It can support regional priority identification and planning but cannot replace parcel-level ownership verification, environmental review, logistics-cost analysis, or engineering feasibility assessment for specific projects.

5.4 Research Outlook

5.4.1 Integration of Multiple Methods

Future research can integrate fuzzy AHP, entropy weighting, TOPSIS, or other multi-criteria decision methods with the AHP-GIS framework. Fuzzy AHP can address linguistic uncertainty in expert judgments, entropy weighting can provide objective information based on data variation, and TOPSIS can rank areas according to their distance from an ideal solution. Combining subjective and objective weighting can test whether key factors and priority areas remain consistent across methods.

Future models could also apply non-compensatory thresholds to factors with strict minimum requirements, such as excessive slope, water-environment protection, and statutory land-use restrictions.

5.4.2 Dynamic Supply-Chain Data

Future studies should incorporate dynamic operational data, including actual road speeds, vehicle scheduling, node-processing capacity, cold-storage capacity, transportation frequency, loading and unloading time, product loss, and market price. Spatial travel time represents only one component of supply-chain performance, while actual service quality also depends on congestion, capacity, and organizational efficiency.

The integration of Internet of Things sensors, traceability platforms, and real-time monitoring data could improve cold-chain information sharing, process traceability, and coordination among stakeholders (Y. Bai et al., 2023; Mugiyo et al., 2021).

With these data, the current spatial suitability model can be extended toward supply-chain performance evaluation. Scenario analysis could compare the effects of new cold-chain nodes, road improvements, changing market demand, or increasing transportation costs on both site suitability and logistics efficiency. Multi-temporal remote-sensing data could also be used to identify actual vegetable-growing areas and seasonal change, allowing production-space data to be dynamically matched with logistics data.

5.4.3 Decision Support System

A future decision support system could integrate growing areas, road networks, logistics nodes, cold-chain facilities, market demand, and territorial spatial constraints. The system could support indicator queries, weight adjustment, scenario simulation, candidate-area comparison, and logistics-route analysis.

Government agencies could use such a system to identify logistics gaps in production clusters, compare cold-chain facility construction alternatives, and coordinate agricultural, transportation, commercial, and land-use planning. Agricultural operators could use it to screen candidate production areas according to crop type, target market, and transportation mode and to compare supply-chain time and cost among locations.

By regularly updating road, facility, production, and market data, suitability evaluation could shift from a one-time static map to a dynamic decision tool. The ultimate objective would not only be to determine where vegetables can be grown, but also to determine where they should be grown, which nodes should serve them, which cold-chain mode should be used, and how products can reach markets more efficiently.

In summary, this study provides an analytical framework that integrates production conditions and supply-chain efficiency for vegetable growing-area selection in Tonghai County. Further improvements in data accuracy, operational supply-chain data, and scenario analysis could strengthen the model's value for agricultural planning, logistics-network design, cold-chain development, and business decision-making.



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APPENDIX

APPENDIX A

中国云南省通海县蔬菜种植区选址——层次分析法专家问卷调查 Selecting the Vegetable Growing Areas in Tonghai County, Yunnan Province, China

AHP Expert Questionnaire

A. 知情同意书

A. Informed Consent Form

引言

当前，农业高质量发展与国土空间优化已成为区域可持续发展的重要议题，蔬菜种植区的合理布局也越来越受到关注。科学的种植区选址不仅关系到土地资源的高效利用、农业基础设施配置和生产成本控制，也影响生态保护、农业风险防控及区域农业长期发展。通海县是云南省重要的蔬菜生产地区，其种植空间布局受到地形地貌、气候条件、水资源、交通可达性及生态约束等多重因素影响。尽管相关研究表明 GIS 与多准则决策方法可为农业空间选址提供技术支持，但不同评价指标的重要性仍需结合地方实际和专家经验加以判断。本研究拟通过专家问卷收集对通海县蔬菜种植区选址评价指标相对重要性的判断结果，用于层次分析法（AHP）权重计算，并为后续 GIS 适宜性评价提供依据。

Introduction

Currently, high-quality agricultural development and the optimization of territorial space have become critical issues for regional sustainable development, and the rational layout of vegetable-growing areas is receiving increasing attention. The scientific selection of growing areas not only affects the efficient use of land resources, the allocation of agricultural infrastructure, and the control of production costs, but also impacts ecological conservation, agricultural risk prevention and control, and the long-term development of regional agriculture. Tonghai County is a major vegetable-producing region in Yunnan Province, and the spatial layout of its cultivation areas is influenced by multiple factors, including topography, climate conditions, water resources, transportation accessibility, and ecological constraints. Although relevant

studies indicate that GIS and multi-criteria decision-making methods can provide technical support for agricultural site selection, the relative importance of different evaluation indicators still needs to be determined based on local conditions and expert experience. This study aims to collect expert assessments of the relative importance of evaluation indicators for vegetable cultivation site selection in Tonghai County through an expert questionnaire. These results will be used for weight calculation via the Analytic Hierarchy Process (AHP) and will provide a basis for subsequent GIS suitability assessments.

1.研究项目名称：中国云南省通海县蔬菜种植区选址

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1. Research project name: Selecting the Vegetable Growing Areas in Tonghai County, Yunnan Province, China

Name of researcher: Miss. Xinyu Zhou

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2.研究目的：本研究旨在收集专家对通海县蔬菜种植区选址评价指标相对重要性的判断，用于计算层次分析法（AHP）权重，并为后续 GIS 适宜性分析提供依据。

2. Research Objective: This study aims to collect expert judgments on the relative importance of evaluation indicators for vegetable planting area site selection in Tonghai County, to calculate Analytic Hierarchy Process (AHP) weights and provide a basis for subsequent GIS suitability analysis.

3.参与说明:

- 参与需求: 本研究邀请在农业生产、土地利用规划、土壤与水资源、物流与供应链(含冷链)及当地农业管理等相关领域具有专业知识或实践经验的专家参与问卷调查,以获取对通海县蔬菜种植区选址评价指标相对重要性的专业判断。

- 纳入标准: 年满18岁;满足至少一项专家资格(相关领域副高及以上职称/相关研究或实践经验超过10年/县级及以上规划或政策制定核心参与);愿意完成本问卷并通过邮件回邮。

- 排除标准: 未满18周岁,或无法/不愿提供知情同意的受试者将被排除。

- 预计参与者人数: 9名专家。

3. Participation Information:

- Participation Requirement: This study invites experts with professional knowledge or practical experience in fields such as agricultural production, land-use planning, soil and water resources, logistics and supply chains (including cold chains), and local agricultural management to participate in the survey, to obtain professional judgments on the relative importance of evaluation indicators for vegetable planting area site selection in Tonghai County.

- Inclusion Criteria: Aged 18 years or above; meeting at least one expert qualification criterion (associate senior title or above in a relevant field / more than 10 years of relevant research or practical experience / core participation in county-level or above planning or policymaking); willing to complete this questionnaire and return it by email.

- Exclusion Criteria: Participants under 18 years of age, or those who are unable or unwilling to provide informed consent, will be excluded.

- Expected Number of Participants: 9 experts.

4. 问卷描述：本问卷为基于层次分析法（AHP）设计的专家调查问卷，共包含 A–G 七个部分。其中，A–C 为研究说明、背景信息及填写指导，D–E 为评价指标的两两比较矩阵，F 为生态约束条件确认，G 为补充意见与建议。

4. Questionnaire Description: This questionnaire is an expert survey questionnaire designed based on the Analytic Hierarchy Process (AHP), and it consists of seven parts, A–G. Among them, Parts A–C provide research information, background information, and instructions for completion; Parts D–E are pairwise comparison matrices of evaluation indicators; Part F is for confirmation of ecological constraints; and Part G is for supplementary comments and suggestions.

5. 填写建议：请根据层次分析法（AHP）1–9 标度进行判断并作答，具体填写方法详见 C 部分说明。

5. Instructions for Completion: Please make judgments and respond according to the 1–9 scale of the Analytic Hierarchy Process (AHP). Detailed instructions for completion are provided in Part C.

6. 保密与数据管理：本研究将对问卷数据进行匿名编号处理，仅用于学术研究，并以汇总形式呈现研究结果，不披露任何个人身份信息。问卷通过电子邮件回邮时，研究团队可能看到参与者的邮箱地址；但在数据整理与分析阶段，将以匿名编号替代任何可识别信息。

- 数据保存：电子文件将保存在研究团队的设备中加密保存，仅研究团队可访问。

- 数据保留与销毁：研究结束后，相关数据将根据学校要求保留 5 年，用于学术审计与复核；保存期满后，电子文件及其备份将被永久删除。

6. Confidentiality and Data Management: The questionnaire data in this study will be processed using anonymous identification numbers and will be used only for academic research. The research results will be presented in aggregated form, and no personal identifying information will be disclosed. When the questionnaire is returned by email, the research team may be able to see the participant's email address; however, during the stages of data organization and analysis, anonymous identification numbers will replace any identifiable information.

- **Data Storage:** Electronic files will be stored in encrypted form on the research team's devices, and only the research team will have access to them.

- **Data Retention and Destruction:** After the completion of the study, the relevant data will be retained for 5 years in accordance with university requirements for academic audit and review; after the retention period expires, the electronic files and their backups will be permanently deleted.

7. 参与者权利：参与完全自愿。参与者可在回邮问卷前任何时间停止填写或选择不回邮，无需说明理由，且不会影响参与者的学习或工作评价、应享权利或与研究者及其机构的关系。参与者在问卷回邮后，如希望撤回其数据，可在数据分析开始前通过电子邮件联系研究者提出撤回申请；撤回后，其数据将被删除且不纳入分析。

7. **Participant Rights:** Participation is entirely voluntary. Participants may stop completing the questionnaire at any time before returning it, or choose not to return it, without giving any reason, and this will not affect their study or work evaluation, their entitled rights, or their relationship with the researcher and the researcher's institution. After returning the questionnaire, if participants wish to withdraw their data, they may contact the researcher by email to request data withdrawal at any time before data analysis begins; once withdrawn, their data will be deleted and will not be included in the analysis.

8. 获益与风险：本研究对参与者通常无直接经济或个人收益，但研究结果将为通海县蔬菜种植区科学选址及空间规划提供参考。本研究属于最小风险研究，参与过程中原则上不会对参与者造成身体、心理、社会或法律风险。

8. **Benefits and Risks:** This study generally provides no direct economic or personal benefit to participants; however, the research results will provide a reference for the scientific site selection and spatial planning of vegetable planting areas in Tonghai County. This study is a minimal-risk study, and in principle, participation will not cause physical, psychological, social, or legal risks to participants.

9. 风险防范与帮助措施:

- 风险防范措施: 研究者将严格保护参与者隐私, 不泄露任何个人身份信息。调查所收集的信息仅供研究团队访问, 研究成果仅以总体分析结果形式呈现, 不涉及披露个人意见或可识别信息。

- 帮助与咨询渠道: 若参与者在填写问卷过程中感到不适、疑惑, 或希望进一步了解研究相关信息, 可随时联系研究者或那黎宣大学人类研究伦理审查委员会。

9. Risk Prevention and Support Measures:

- Risk Prevention Measures: The researcher will strictly protect the privacy of participants and will not disclose any personal identifying information. The information collected through this survey will be accessible only to the research team, and the research results will be presented only in the form of overall analysis results, without disclosing individual opinions or identifiable information.

- Support and Consultation Channels: If participants feel uncomfortable or confused during the completion of the questionnaire, or wish to obtain further information about the study, they may contact the researcher or the Naresuan University Human Research Ethics Committee at any time.

10. 预计作答时间: 填写本问卷预计需要约 10–15 分钟。

10. Estimated Time Required: Completing this questionnaire is expected to take approximately 10–15 minutes.

11. 联系信息:

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Postal code: 65000

12.知情同意：本问卷不收集签名。若参与者已阅读上述说明，并在收到本研究邀请后的 14 天内完成问卷并通过电子邮件回邮，即表示您已理解研究内容并自愿同意参与本研究。感谢您的支持与配合！

12. Informed Consent: No signature is required for this questionnaire. If participants have read the above information, complete the questionnaire within 14 days after receiving the research invitation, and return it by email, this will indicate that they have understood the research content and voluntarily agree to participate in this study. Thank you for your support and cooperation!

同意声明 Consent Statement	
资格确认 Eligibility Verification	☐ 我已年满 18 岁且符合专家资格 ☐ I am 18+ and meet the expert criteria
知情同意确认 Informed Consent Confirmation	☐ 我同意参与本研究 ☐ I agree to participate
日期 Date	日期 Date: _____

B. 专家基本信息

请填写下列信息，仅用于描述样本特征，不作为个人身份识别信息。

B. Expert Background Information

Please complete the following for sample description only. Do not provide sensitive identifiers.

专家类别 Expert category	☐ 农业种植专家 Agriculture growing ☐ 土壤与水资源专家 Soil and water resources ☐ 土地利用与规划专家 Land use and planning ☐ 物流与供应链专家 Logistics and supply chain ☐ 当地农业管理/技术人员 Local agricultural administrator/technical staff
专家资格条件 (至少满足一项) Expert qualification (meet at least one)	☐ 相关领域副高及以上职称 Associate senior or above ☐ 相关研究或实践经验超过 10 年 More than 10 years' experience ☐ 县级及以上规划/政策制定核心参与 Core involvement in planning/policy development at the county level and above
所在单位类型 Organization type	☐ 政府 Government ☐ 高校/科研 Academic/Research ☐ 企业 Company ☐ 协会/行业组织 Association/Industry body ☐ 其他 Other: _____

相关领域从业年限 Years of relevant experience	_____ 年 years
是否参与县级及以上 规划/政策制定（核 心成员） Core involvement in planning/policy development at the county level and above (Yes/No)	☐ 否 No ☐ 是 Yes，说明 Please specify（机构/层级/年份 org-level-year）： _____
是否熟悉通海县或云 南农业与流通背景 Familiar with Tonghai/Yunnan context	☐ 是 Yes ☐ 否 No
备注（可选） Notes (optional)	_____

C. AHP 1–9 标度说明

在成对比较中，若 A 相对于 B 更重要，请在对应空格填写 2–9 的数字；若两者同等重要填写 1。数字越大表示 A 相对于 B 越重要。若您认为 B 更重要，请按 A 相对于 B 的方向填写倒数，例如 1/3 表示 B 比 A 重要 3 倍。

C. AHP 1–9 Scale Guide

In pairwise comparisons, if item A is more important than item B, enter a number from 2 to 9. Enter 1 if they are equally important. Larger numbers mean A is more important than B. If B is more important, enter the reciprocal in the A versus B direction, e.g., 1/3 means B is 3 times more important than A.

数值 Value	含义 Meaning
1	同等重要 / Equal importance
3	稍微重要 / Moderate importance
5	明显重要 / Strong importance
7	非常重要 / Very strong importance
9	极端重要 / Extreme importance
2 4 6 8	中间值 / Intermediate values
1/2–1/9	对方更重要时填倒数 / Reciprocals when the column item is more important

填写规则：仅需填写对角线以上右上三角空格；对角线固定为 1；其余倒数项由研究者在数据整理时补齐。

Filling rule: Fill only the blanks in the upper triangle. Diagonal entries are 1. The investigator will compute reciprocals during data processing.

D. 准则层成对比较：用于计算准则权重

说明：论文方法中生态因素作为强约束在 GIS 阶段处理，不纳入 AHP 权重计算。本部分仅比较自然、经济与社会三类准则的重要性。

D. Criteria-level Pairwise Comparisons for criteria weights

Note: In the thesis method, ecological factors are treated as non-compensatory constraints in the GIS phase and are not included in AHP weight calculations. This section compares only Natural, Economic and logistics, and Social criteria.

行相对列 Row vs Column	自然因素 Natural	经济 Economic	社会因素 Social
自然因素 Natural	1	_____	_____
经济 Economic	研究者填写 Filled by investigator	1	_____
社会因素 Social	研究者填写 Filled by investigator	研究者填写 Filled by investigator	1

E1. 指标层成对比较:自然因素

定义: 坡度越小越适宜; 年均温为区间型指标; 土壤有机质越高通常越有利于产量与土壤质量。

E1. Indicator-level Pairwise Comparisons: Natural factors

Definitions: Slope is more suitable when smaller. Annual average temperature is an interval-type indicator. Higher soil organic matter generally benefits yield and soil quality.

行相对列 Row vs Column	C1 坡度 Slope	C2 年均温 Annual average temperature	C3 土壤有机质 Soil organic matter
C1 坡度 Slope	1	_____	_____
C2 年均温 Annual average temperature	研究者填写 Filled by investigator	1	_____
C3 土壤有机质 Soil organic matter	研究者填写 Filled by investigator	研究者填写 Filled by investigator	1

E2. 指标层成对比较:经济因素

定义: 上述均为成本型指标, 行程时间越短通常越有利于运输效率、损耗控制与冷链衔接。

E2. Indicator-level Pairwise Comparisons: Economic factors

Definitions: All are cost-type indicators. Shorter travel times generally improve transport efficiency, reduce losses, and enhance cold-chain connectivity.

行相对列 Row vs Column	C4 到高速国道省 道行程时间 Travel Time to Expressway/ National/ Provincial Highway	C5 到县级批发物 流枢纽行程时 间 Travel time to county wholesale and logistics hub	C6 到冷库预冷加 工点行程时间 Travel time to cold storage pre-cooling processing points	C7 到核心外销 市场行程时 间 Travel time to core export markets
C4 到高速国道省 道行程时间 Travel Time to Expressway/ National/ Provincial Highway	1	_____	_____	_____
C5 到县级批发物 流枢纽行程时 间 Travel time to county wholesale and logistics hub	研究者填写 Filled by investigator	1	_____	_____

C6 到冷库预冷加工点行程时间 Travel time to cold storage pre-cooling processing points	研究者填写 Filled by investigator	研究者填写 Filled by investigator	1	_____
C7 到核心外销市场行程时间 Travel time to core export markets	研究者填写 Filled by investigator	研究者填写 Filled by investigator	研究者填写 Filled by investigator	1

E3. 指标层成对比较：社会因素

定义：劳动力密度就业比例越高通常越有利于稳定生产；公共服务设施可达时间越短通常越有利于生产与生活支撑。

E3. Indicator-level Pairwise Comparisons Social factors

Definitions: Higher agricultural labor density or employment ratio generally supports stable production. Shorter access time to public service facilities generally improves support conditions.

行相对列 Row vs Column	C8 农业劳动力密度就业比例 Agricultural labor density employment ratio	C9 农村公共服务设施可达性 Rural public service accessibility
C8 农业劳动力密度就业比例 Agricultural labor density employment ratio	1	—
C9 农村公共服务设施可达性 Rural public service accessibility	研究者填写 Filled by investigator	1

F. 生态约束确认(不参与权重计算)

本研究将以下生态因素作为 GIS 阶段强约束 0/1 掩膜，用于直接排除不符合要求的区域。请确认这些约束是否合理，或提出建议。

F. Ecological Constraints (Confirmation not weighted)

The following ecological factors are treated as non-compensatory constraints in the GIS phase using Boolean masks to exclude unsuitable areas. Please confirm their appropriateness or provide suggestions.

约束项 Constraint item	确认 Confirm	备注 Notes
C10 生态保护红线/自然保护地 Ecological protection redlines/Nature reserves	☐ 合理 Yes ☐ 不确定需调整 Unsure adjust	_____
C11 饮用水水源保护区及缓冲区 Drinking water source protection areas and buffer zones	☐ 合理 Yes ☐ 不确定需调整 Unsure adjust	_____
C12 永久基本农田 Permanent basic farmland	☐ 合理 Yes ☐ 不确定需调整 Unsure adjust	_____
总体建议(可选) Overall comments (optional)	_____	_____

G. 提交与回邮说明

请完成 B 部分基本信息、D 与 E 部分所有矩阵空格，并可选填写 F 部分建议。完成后请将本文件作为附件回邮给研究者。

填写提示：若您认为列指标更重要，请填写倒数例如 1/3、1/5。请尽量避免空题；如确实无法判断，可在对应格写 NA。

G. Submission and Return Instructions

Please complete Section B background, all blank cells in matrices in Sections D and E, and optional Section F comments. Then return this file as an email attachment to the investigator.

Tip: If the column item is more important, write the reciprocal such as 1/3 or 1/5. Please avoid leaving blanks. If you cannot judge, write NA in the cell.